GEOLOGY OF THE CRETACEOUS-TERTIARY(?) ROCKS OF THE SOUTHWEST QUARTER OF THE MONTE GUILARTE QUADRANGLE, WEST-CENTRAL PUERTO RICO

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ABSTRACT

The southwest quarter of the Monte Guilaerte quadrangle in west central Puerto Rico covers an area of about 50 square kilometers. It is located about 8 kilometers south of the southern Puero Rico fault zone. This shear zone is a northwest-southeast trending lineament which divides the central block of the island from the southern block. The oldest rock unit in the area is the Rio Loco Formation which consists mainly of pillowed basaltic lava flows, flow breccias, hyaloclastite deposits, volcaniclastic breccias and conglomerates,and minor calcareous sedimentary rocks and limestone lenses. The rocks are Upper Cretaceous and were deposited subaqueously.

The Maricao Basalt, which is in fault contact with the Rio Loco Formation, comprises about 1,300 meters of massive augite-rich volcaniclastic breccias and conglomerates, sandstones, and subordinate calcareous sedimentary rocks, basaltic lava flows, and limestone. The unit is Campanian to Maestrichtian in age. The principal sources of the volcaniclastic material were pre-existing rocks which were exposed subaerialy and were being eroded. The sediments were rapidly buried preventing further reworking.

The Yauco Mudstone, which unconformably overlies the Maricao Basalt, consits of about 360 meters of thin- to medium-bedded calcareous volcaniclastic sand-

stones and siltstones, claystones, limestones, and minor calcareous conglomerates and breccias, and tuffs. The unit is Campanian to Maestrichtian, but maybe possibly in part as old as Turonian. The principal source of the Yauco volcaniclastic material was pre-existing volcanic and hypabyssal rocks. The sediments were deposited in a shallow-water marine environment which was tectonically unstable; this resulted in widespread accumulations in southwestern Puerto Rico. The Yauco Mudstone is conformably overlain by an unnamed hornblende breccia unit in one part of the area and by the Sabana Grande Formation in another area.

The unnamed hornblende breccia unit consists mainly of hornblende-rich volcaniclastic breccias and conglomerates with minor interbeds of calcareous volcaniclastic sedimentary rocks. The unit is Campanian, probably Turonian, to Maestrichtian in age. The source of the sediments was pre-existing rocks which were exposed to the east and/or north. The overall tectonic environment of this unit is similar to that of the Yauco Mudstone.

The Sabana Grande Formation consists mainly of amygdaloidal, massive, basaltic, lava flows with minor flow breccias and pyroxene-rich sandstones. It has been assigned a Turonian to Campanian age but based on paleontological data obtained during this investigation,the unit may be as young as Maestrichtian. The unit was extruded subaerially and since it is con cordant within the Yauco Mudstone it indicates that the basin of Yauco deposition in this area was extremely shallow with periods of exposure above sea level.

The entire volcanic-sedimentary sequence was intruded in late Cretaceous to early Tertiary time by augite porphyry and hornblende porphyry bodies. During or after Maestrichtian time the area was deformed into large open folds. Later, faulting became the predominant type of deformation. Vertical faults are apparently more common than other types.

The small amount of lava flow, except in the Rio Loco Formation and Sabana Grande Formation, and little pyroclastic material in the sedimentary units strongly indicates that little explosive volcanic activity was going on during deposition of the units. The abundance of volcanic, hypabyssal, and igneous rock fragments in the sediments indicates that the main sources of the sediments were pre-existing rocks. The presence of unpillowed lava flows within the sedimentary units suggests that the sediments were deposited in a shallow water area with periods of exposures above sea level. Paleogeographic evidence indicates that the overall source of the sediments was probably to the north and/or east.

The presence of felsic rock fragments in the upper part of the sequence is evidence that felsic source rocks were exposed. Apparently the island arc was mature by Late Cretaceous time with andesite and dacite the dominant rock types.

Veiw of part of the southwest quarter of the
Monte Guilarte quadrangle, looking northwest
from a hill south of Hacienda Arbela.

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INTRODUCTION

The geology of an island arc presents a challenge to geologists. The combination of sedimentary, volcanic, intrusive, and tectonic processes gives rise to a very complex geologic picture which can only be unraveled by detailed geologic mapping. With this in mind the geology of the southwest quarter of the Monte Guilarte quadrangle was studied, providing information on the geologic events which occrred in west-central Puerto Rico during Cretaceous time. The area under consideration covers 50 square kilometers in the east-west trending Cordillera Central.

Puerto Rico is the easternmost of the Greater Antilles (Figure 1), a chain of islands which includes, from west to east, Cuba, Jamaica, Hispaniola, and Puerto Rico. East of Puerto Rico a group of smaller islands make up the Lesser Antilles, which stretches southward in an arc to eastern Venezuela.

The island is an east-west trending rectangle 176 kilometers long and 59 kilometers wide with a surface area of 10,384 square kilometers. It is bordered by the Atlantic Ocean to the north and the Caribbean Sea to the south. The topography of the island is extremely varied, ranging from coastal plains to mountainous interior. The latter consists mainly of the east-west trending Cordillera Central, which forms a drainage divide separating the wet, densely vegetated north

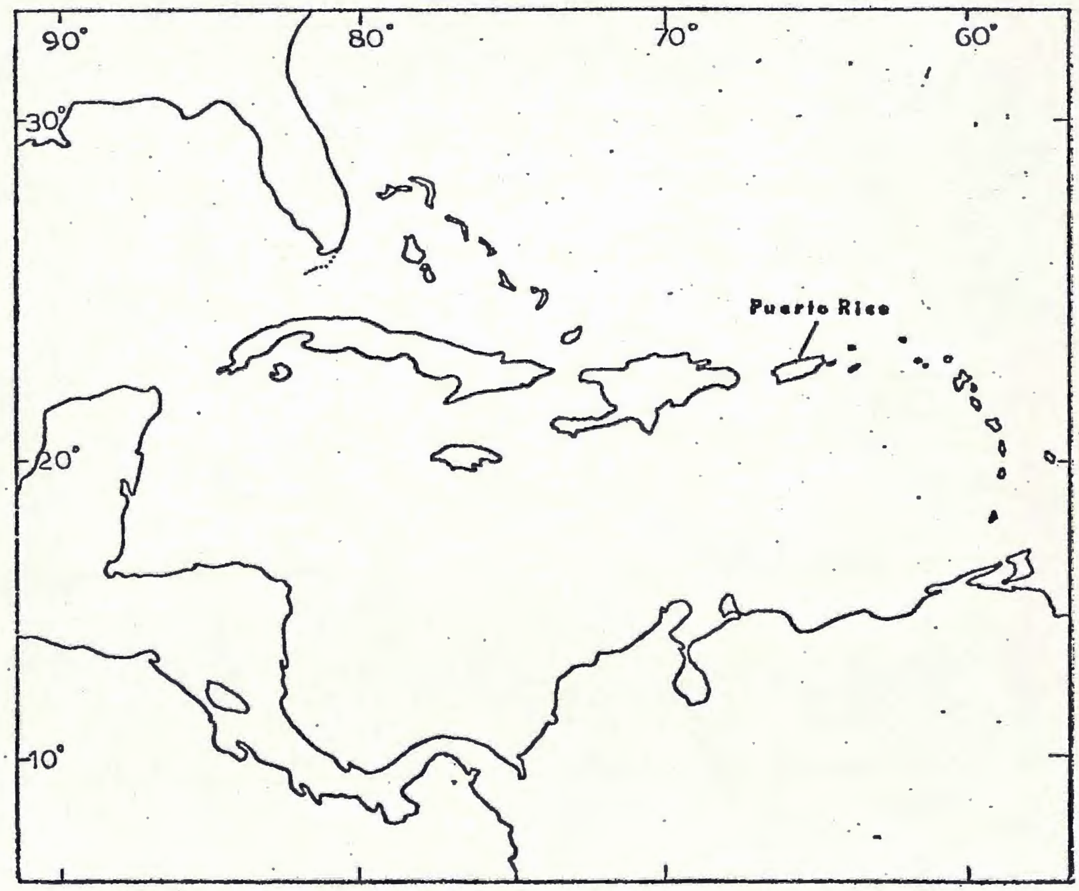

Figure 1. Index map of the Caribbean area showing Puerto Rico.

(windward) side from the dry, less vegetated south (leeward) side. The highest point on this divide is Cerro de Punta with an elevation of 1,338 meters, and it is located about 27 kilometers east of the study area. Typical slopes are from 20 to 35 degrees but 40 to 45 degree slopes are not uncommon. The island has a subtropical marine climate largely controlled by the northeast trade winds. Precipitation varies from about 200 inches in the northeast corner of the island to about 29 inches in the southwest corner. Temperatures range from about 70 to 90°F with no drastic seasonal changes. Tropical rain forest covers most of the highest parts of the island. The southwest corner of the island has a semi-arid climate and an extensive irrigation system is required to make land productive. The area of this report, which is quite accessible by road, is mainly used for agriculture with coffe, bananas, plantains, and citrus fruits the main products.

The geology of the southwest quarter of the Monte Guilarte quadrangle is being studied as part of a program of geologic mapping and investigation of the mineral resources of Puerto Rico conducted by the United States Geological Survey in cooperation with the Department of Natural Resources, Commonwealth of Puerto Rico.

Field work was carried out from June to August, 1975. Field mapping was done on a published topographic map (scale 1:20,000) and on aerial photographs.

The bedrock consists of igneous and sedimentary rocks. The igneous rocks are both intrusive and extrusive, the former being more abundant. The sedimentary rocks are chiefly volcaniclastic breccias, conglomerates, sandstones and siltstones and minor amount of limestones. The area is covered by thick saprolitic soils which are densely vegetated.

REGIONAL GEOLOGY

With the exception of Cuba all of the islands bordering the Caribbean Sea, the northernmost portion of Venezuela and Colombia, and most of Central America belong to the Caribbean plate (Malfait and Dinkleman, 1972). The plate, according to these authors, was originally part of the East Pacific plate which during Mesozoic time wedged between North and South America. The northeastern boundary of the Caribbean plate is the Puerto Rico Trench, which lies about 160 kilometers north of the island. It was a zone of active overthrusting of the Caribbean plate over the adjacent North America plate during Cretaceous and early Tertiary times (Malfait and Dinkleman, 1972). From Eocene to Oligocene time the trench changed from a zone of subduction to a left lateral transform fault.

Although the Caribbean area is highly accessible,it is one of the least understood and most controversial tectonic areas of the world. The reader is referred to Donnelly (1964), Monroe (1968), Skovor (1969), Khudoly and Meyerhoff (1971), Edgar, Ewing, and Hennion (1971), Bell (1971), Malfait and Dinkelman (1972), Mattson (1973), Uchupi (1973), Nagle (1974), and Iturralde-Vinent (1975) for a complete discussion of the history of the Caribbean plate.

Puerto Rico is composed of three east-west trending geologic belts (Figure 2). The northern and southern belts consist mainly of mid-Tertiary limestones. These rocks rest unconformably on the volcanic rocks of the central belt. The volcanic and plutonic rocks range in age from early Cretaceous to Eocene (Nelson, 1968). The limestones of the northern belt dip gently to the north at 5-10 degrees, and in the southern belt they dip gently to the south at 15-30 degrees, partially due to block faulting as the island emerged in middle to late Miocene time (Tobisch, 1968). The limestones in the northern belt have a well developed karst topography which is the result of the high amount of rainfall in the northern part of the island.

The central belt consists of a geanticline made up of a thick pile of volcaniclastic rocks, lavas, and intrusive rocks. This central volcanic core of the island has been divided into three main blocks by large west-northwest trending fault zones (Briggs, 1964). All three of the blocks contain volcanic, volcaniclastic and intrusive rocks; the central block contains the two largest plutonic bodies on the island, the San Lorenzo Batholith and the Utuado Pluton. The southern block contains serpentinites associated with cherts, spilites, and amphibolites (Tobisch, 1968); these rocks crop out at the cores of various anticlines and form the basal complex of the island (Mattson, 1960).

Moderate deformation has occurred in all three blocks and faulting predominates over folding indica-

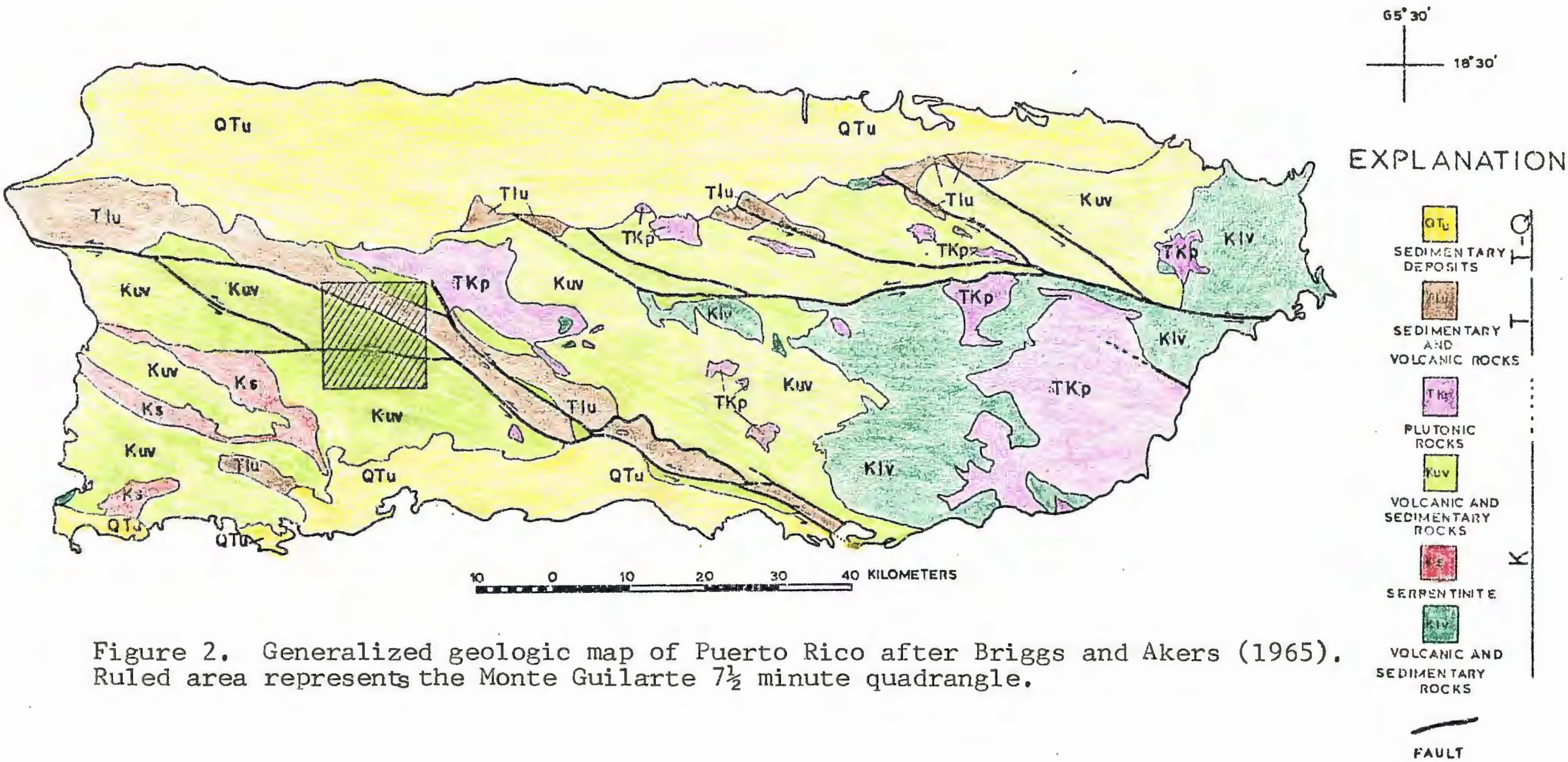

Figure 2. Generalized geologic map of Puerto Rico after Briggs and Akers (1965). Ruled area represents the Monte Guilarte 7½ minute quadrangle.

ting that deformation was brittle. Along the major faults, movement appears to be largely horizontal (left-lateral) with minimum displacement in the order of 4 to 10 kilometers, and minor vertical movement (Briggs and Pease, 1960; Glover, 1971). Folding was probably contemporaneous with faulting. The exsistence of local gravity glides has been demonstrated by Mattson (1960) and Glover (1971).

Low grade regional metamorphism (zeolite facies) has affected most of the volcanic rocks of the central belt (Otalora, 1964; Glover, 1971; Jolly, 1970) and locally greenschist facies is attained (Glover, 1971). Original textures are well preserved in most rocks although some foliation is developed near large fault zones and in the vicinity of intrusive bodies (Glover, 1971).

PREVIOUS WORK

The first geologic work on the island was carried out by Cleve (1871) and Hill (1899). They were responsible for establishing a Cretaceous age for the older complex and noticing the presence of relatively undisturbed rocks of Tertiary age. The next geologic work was a scientific survey of Puerto Rico and the U. S. Virgin Islands by the New York Academy of Sciences from late 1910's to 1920's. Berkey's (1915) geological reconaissance of the island laid the foundation for the survey and the island was studied in more detail by Semmes (1919), Hodge (1920, Mitchell (1922), Hubbard (1923), Fettke (1924), and Meyerhoff and Smith (1931). Meyerhoff (1933) wrote a generalized review based on these reports. Oligocene and Miocene rocks of the northern and southern coastal plains where studied by Zapp, Berquist and Thomas (1948). Mitchell (1954) summarized the literature of the geology of the island.

In the 1950's the United States Geological Survey became involved in systematic mapping of the geology of the island, and nearly all of the 7½ minute topographic quadrangles, scale 1:20000, have been completed at this time (1976).

Slodowski (1956) in his report of the Yauco area covered 6 quadrangles in southwestern Puerto Rico, including part of the Monte Guilarte quadrangle (Figure 3).

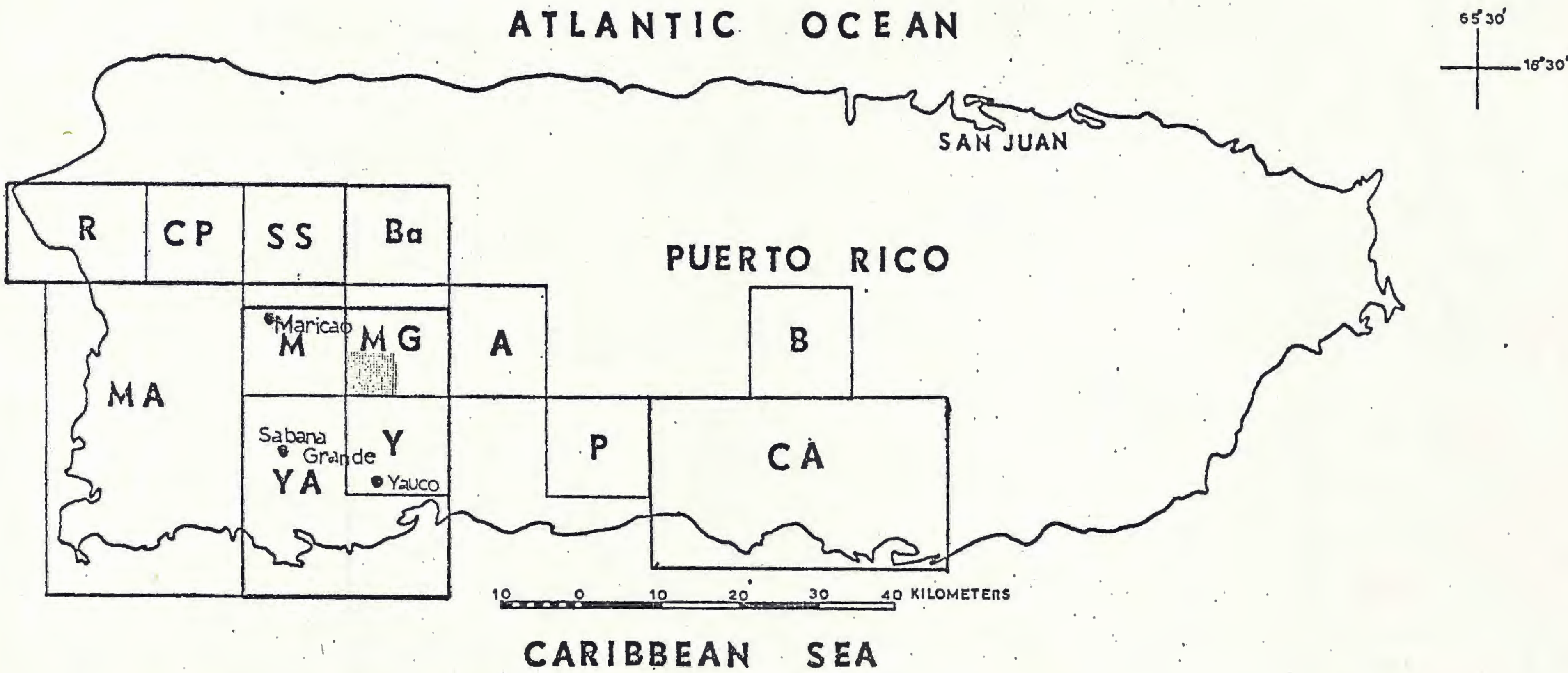

Figure 3. Index map of south-central Puerto Rico. The following quadrangles and areas referred in the text are shown by abbreviations: R, Rincon; CP, Central La Plata; SS, San Sebastian; Ba, Bayaney; MA, Mayaguez area; YA, Yauco area; M, Maricao; MG, Monte Guilarte; A, Adjuntas; B, Barranquitas; Y, Yauco; P, Ponce; CA, Coamo area; shaded area, southwest quarter of the Monte Guilarte quadrangle.

Mattson (1960) mapped the Mayaguez area in the westernmost part of the island. Other geologic work recently carried out in the adjacent areas includes : geology of Ponce-Coamo area (Pessagno, 1960); geology of the Barranquitas quadrangle (Otalora, 1964); petrology of andesitic, spilitic, and keratophyric rocks (Lidiak, 1965); petrology of the Utuado Pluton (Chen, 1967); petrology of the potassium-rich igneous rocks and low grade metamorphism (jolly, 1970, 1971).

All of the quadrangles adjoining the Monte Guilarte quadrangle have been mapped by the United States Geological Survey. These include the Bayaney quadrangle (Nelson and Tobisch, 1968) to the north, the Adjuntas quadrangle (Mattson, 1968) to the east, the Yauco quadrangle (Krushensky, U.S.Geological Survey, in preparation) to the south, and the Maricao quadrangle (McIntyre, 1973, U.S.Geological Survey open file report) to the west.

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Deepest appreciation is expressed to my wife, Annette, and my daughter, Francine, for their understanding, patience, and help during this effort.

DEFINITION OF TERMS

Most of the terminology follows that of Williams, Turner, and Gilbert (1954). Volcaniclastic rocks are commonly divided on the basis of origin and clast size following Fisher's (1961) classification. Limestone classification is generally that of Folk (1962).

Bedding character is described as: massive when there is an absence of planar features throughout 3 meters of stratigraphic section; thick bedded when strata are 50 centimeters to 3 meters thick; medium bedded when strata are 10 to 50 centimeters thick; and thin bedded when srtata are less than 10 centimeters thick.

If the clasts greater than 2 millimeters in diameter are angular and fairly similar in coaposition, the rock is called a breccia; if the clasts are subrounded to rounded and of different lithologies, the rock is called a conglomerate. The terms parabreccia and paraconglomerate are used when the breccia and conglomerate clasts are not touching each other and are completely surrounded by matrix.

The following Spanish nouns are used with geographic names in the text: barrio, a political subdivision of a municipality; cerro, hill; hacienda, large farm or plantation; monte, mountain; quebrada, stream; rio, river; and cordillera, mountain range.

PETROGRAPHIC METHODS

Descriptions of the rocks are based upon field observations and laboratory studies of about 160 samples. One hundred and thirty thin sections were prepared and examined, and one hundred and fifty laquered rock slabs were also examined. Potassium feldspar was detected by sodium cobaltinitrate staining on rock slabs which were first etched in hydrofluoric acid. Plagioclase composition were obtained by the Michel-Levy method. Modal analyses are based on 600 points per thin section; traverses were normal to bedding where bedding was determinable.

STRATIGRAPHY

The rocks of the southwest quarter of the Monte Guilarte quadrangle consist of a sequence of volcanic and sedimentary rocks, the latter made up mainly of reworked volcanic and hypabyssal material. Slodowski (1956) in mapping the Yauco area covered a large area in a relatively short period of time and therefore his mapping is highly generalized. He failed to recognize most of the volcanic and sedimentary units in the area of this report. In this report the rocks are divided into five mappable units (Figure 4, Plate 1). They are from older to younger: the Rio Loco Formation, the Maricao Basalt, the Yauco Mudstone, an unnamed hornblende breccia unit, and the Sabana Grande Formation. Into these rocks, dikes, sills, and plugs of the augite porphyry and the hornblende porphyry have been intruded (Figure 5, Plate 1). All of these units, with the possible exception of the intrusive bodies, are Upper Cretaceous in age. Faulting, thick vegetation, and deep weathering complicate the geologic mapping.

Age	Formation	Description
UPPER CRETACEOUS	SABANA GRANDE FORMATION	Massive basaltic lava flows with minor sandstones.
	UNNAMED HORNBLENDE BRECCIA UNIT	Hornblende-bearing volcaniclastic breccias and conglomerates with minor calcareous sediments.
	YAUCO MUDSTONE	Calcareous volcaniclastic sandstones and siltstones, mudstones, and minor calcareous breccias and tuffs.
	MARICAO BASALT	Augite-bearing volcaniclastic breccias and conglomerates with minor sandstones, lava flows, and calcareous sedimentary rocks.
	RIO LOCO FORMATION	Pillowed lavas, brecciated flows, hyalloclastite, volcaniclastic breccias and minor calcareous sedimentary rocks.

Figure 4. Generalized geologic column of the southwest quarter of the Monte Guilarte quadrangle.

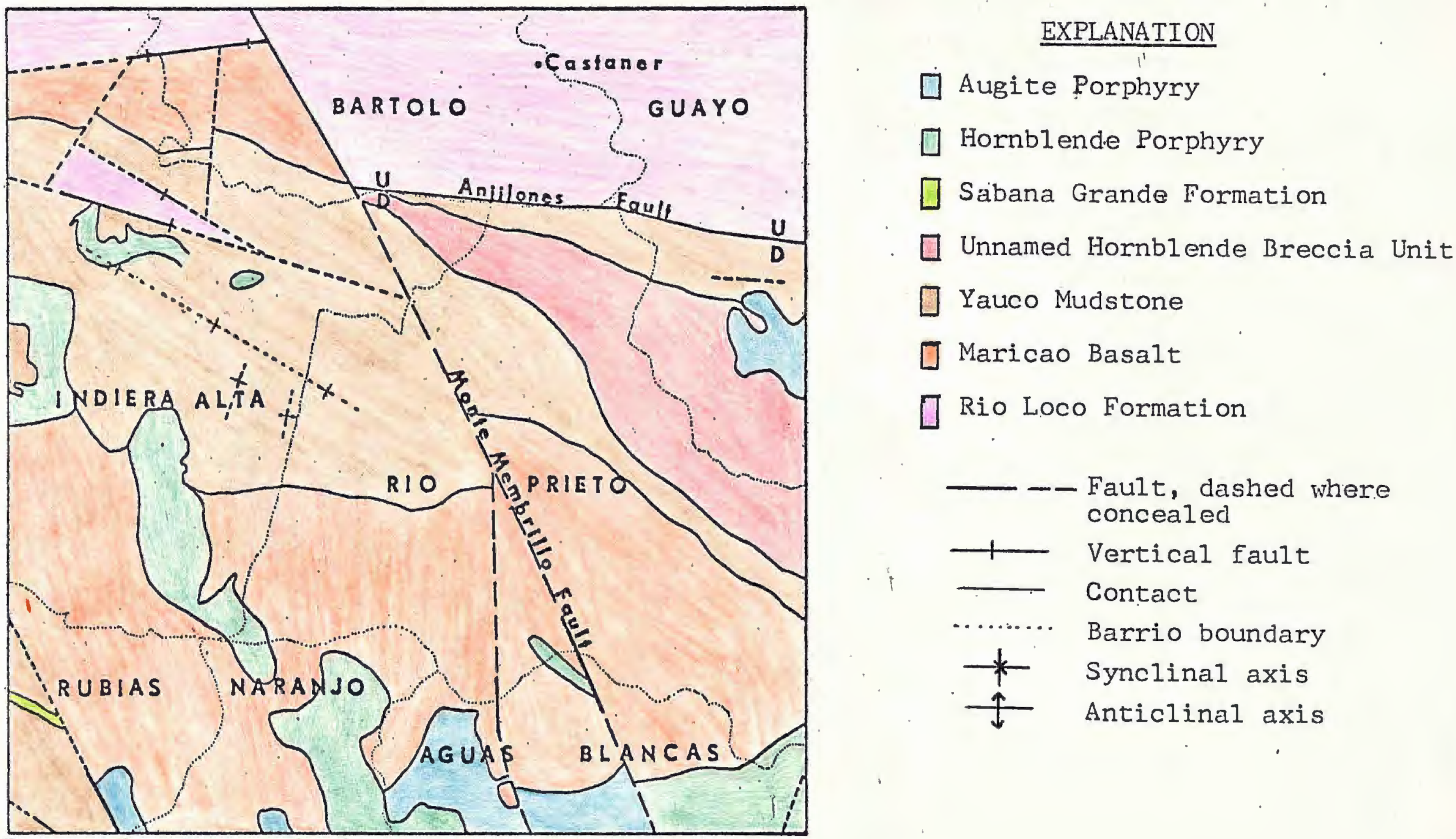

Figure 5. Generalized geologic map of the southwest quarter of the Monte Guilarte quadrangle.

RIO LOCO FORMATION

Slodowski in his report of the Yauco area described this unit as the Rio Blanco Formation. However, the formation which was previously named the Rio Blanco Series by Hubbard (1923) and redefined by Slodowski (1956), has been found to be correlative with rocks of Tertiary age (Mattson, 1967). On this basis Mattson suggested that "the name Rio Blanco be abandoned in favor of other names appropiate to the specific areas" (Mattson, 1967, p. B24). Therefore, the rocks named Rio Blanco shall be considered here to be the Rio Loco Formation.

The Rio Loco Formation was named by Slodowski (1956) for rocks exposed near the towns of Sabana Grande and Yauco (Figure 3). He described the rocks as:

> "... hypersthene basalt porphyry and fine-grained, vitric and crystal tuffs. A thin conglomerate is locally at the base" (Slodowski, 1956, p. 53).

In the Mayaguez area Mattson (1960) described the unit as being made up of bronzite andesite porphyry lavas (some pillowed) and minor tuffs, breccias, hornblende andesites, dacites and limestones. Otalora (1961) in his report of the Barranquitas quadrangle mentions that the name hypersthene basalt porphyry is confusing since the dominant mafic phenocryst is augite. In the adjacent Maricao quadrangle the unit is made up mainly of amygdular, pillowed andesite flows with clinopyroxene, plagioclase, and altered orthopyroxene (McIntyre, 1973).

The Rio Loco Formation covers about 15 percent of the area mapped and occurs in the northernmost part in Barrio Guayo, Barrio Bartolo, and in the north of Barrio Indiera Alta. The unit extends north, east and west beyond the boundaries of the area.

Only one sample collected from the formation contained Foraminifera. The fossils were identified by C. C. Smith of the U. S. Geological Survey, as follows:

Lithology: Limestone (8/5/75-1)

Fauna: Rugoglobina rugosa (Plummer)

Age: Early (but not earliest) Campanian through Late Maestrichtian.

Slodowski (1956) also obtained only one sample which contained Foraminifera and its age was determined to be Maestrichtian. Mattson (1960) found no fossils in the unit but inferred a Cenomanian age. McIntyre (1973) offered no paleontologic data but based on stratigraphic relationships, the unit was assigned an Upper Cretaceous (pre-Campanian) age. The lack of paleontologic data makes it impossible to determine a precise age; the unit will be considered to be of Upper Cretaceous, at oldest Campanian age.

Bedding is sparse and varies considerably in attitude. The lack of knowledge of the structure of the unit does not permit a meaningful estimate of its thickness. Slodowski (1956) estimated a thickness of about 350 meters; in the Mayaguez area the unit was estimated to be at least 300 meters thick (Mattson, 1960), and in the Barranquitas quadrangle Otalora (1961) estimated a thickness of about 1,000 meters but pointed out that the base was not exposed.

Rock descriptions

The Rio Loco Formation in the southwest quarter of the Monte Guilarte quadrangle consists mainly of deep purplish-brown to light greenish-gray (when fresh) basaltic lava flows; dark greenish-brown to light brownish-purple volcaniclastic breccias and conglomerates; minor light brown calcareous sandstones, siltstones, and breccias with minor limestone lenses.

The basaltic lava flows are locally pillowed (Figure 6). An excellent outcrop occurs on road 135 about 1.2 kilometer east of the town of Castaner, in Barrio Guayo. The pillows are ellipsoidal, up to 1 meter in length and about 0.5 meter wide and they are about in their original positions. The interstices are filled with a light purplish-brown, fine-grained limestone.

In the outcrops along the Rio Prieto dam, 800 meters west of the intersection of roads 128 and 431 in the northern part of Barrio Indiera Alta, the unit consists of brecciated lava flows with all of the clasts having a similar composition, in a fine-grained calcareous matrix. Some isolated pillows up to 0.5 meter

Figure 6. Outcrop of pillowed lavas of the Rio Loco Formation, about 2.4 kilometers east of the town of Castaner on road 135. Hammer (25 centimeters long) in center for scale.

Figure 7. Outcrop of the hyaloclastite deposit of the Rio Loco Formation along the Rio Prieto dam. A pillow is at lower left. To the right is the brecciated lava flow.

in length are present here (Figure 7). Beds of calcareous tuffaceous sandstones up to 0.5 meter thick are interbedded with the brecciated lavas, and they show signs of distortion due to the deposition of the overlying brecciated flows, indicating that the sediments were soft enough to be deformed but competent enough to act as a single layer. Calcareous sediments seem to have been broken and incorporated into the brecciated flows. The rocks in this outcrop can be classified as a hyaloclastite deposit (Rittman, 1962).

The lavas are dominantly hypocrystalline, aphanitic to fine-grained, porphyrytic, basaltic in composition, and are made up of about 5 to 10 percent anhedral to subhedral augite phenocrysts in a groundmass which ranges in texture from trachytic to pilotaxitic and is composed of oxidized glass and euhedral, commonly sericitized plagioclase laths up to 0.5 millimeter in length. At some localities about 2 to 5 percent of the rock is made up of ferromagnesian phenocrysts which have been completely replaced by epidote, calcite and an unidentified light greenish-yellow alteration mineral (Figures 8 and 9). The lavas are commonly amygdular with amygdules making as much as 35 percent of the rock; calcite, chlorite, quartz, and zeolites are the main minerals in the amygdules. In one locality an orthopyroxene phenocryst was noticed; it was biaxial (-), had parallel extinction and a 2V of

Table 1.

MODAL ANALYSES OF THE RIO LOCO LAVAS

	8/4/75-4	7/29/75-2	7/18/75-6
Phenocrysts			
Augite	-	1.7	-
Altered Ferromag.	0.9	-	4.9
Opaques	6.8	3.8	-
Groundmass	-	-	95.0
Plagioclase	53.5	58.2	-
Augite	-	13.7	-
Orthopyroxene	-	0.9	-
Alteration	38.7	21.6	-
	99.9	99.9	99.9
Percent of amygdules in the rock.	13	tr	33

7/18/75-6 Lava of the Rio Loco Formation from outcrops around the Rio Prieto dam in the Rio Prieto, about 1 kilometer west of the intersection of roads 128 and 431.

7/29/75-2 Lava of the Rio Loco Formation from an outcrop on a small trail 1 kilometer west of Hacienda Maria Antonia in Barrio Indiera Alta.

8/4/75-4 Lava of the Rio Loco Formation from outcrops on road 374 south of the town Castaner, on kilometer 1.0.

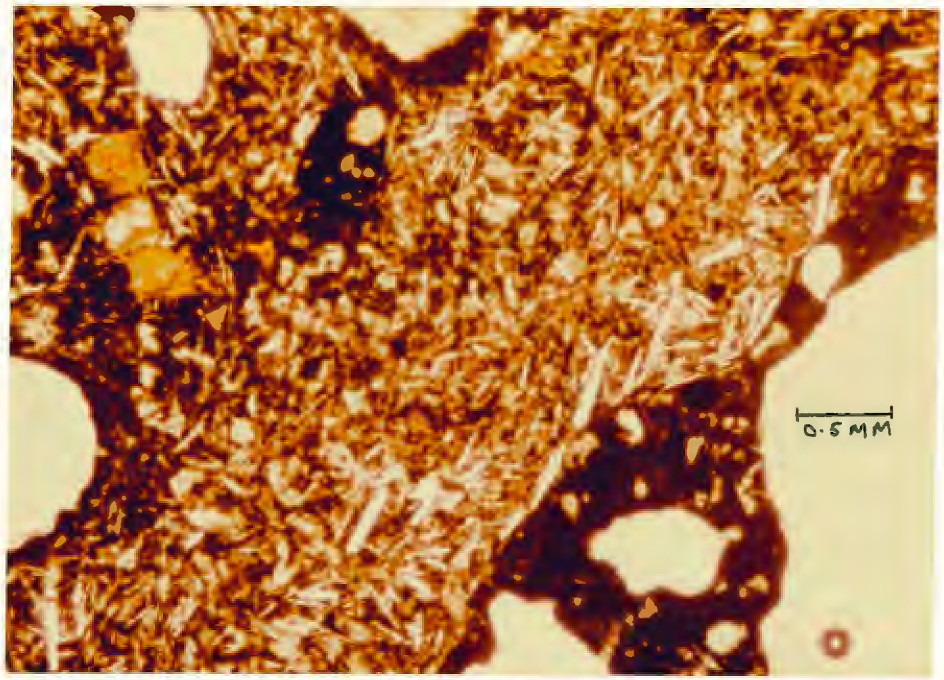

Figure 8. Sample 7/18/75-6 Photomicrograph of a lava flow of the Rio Loco Formation. Light brown crystals are altered ferromagnesian phenocrysts in an oxidized matrix with trachytic plagioclases. White patches are calcite in amygdules. Crossed nicols.

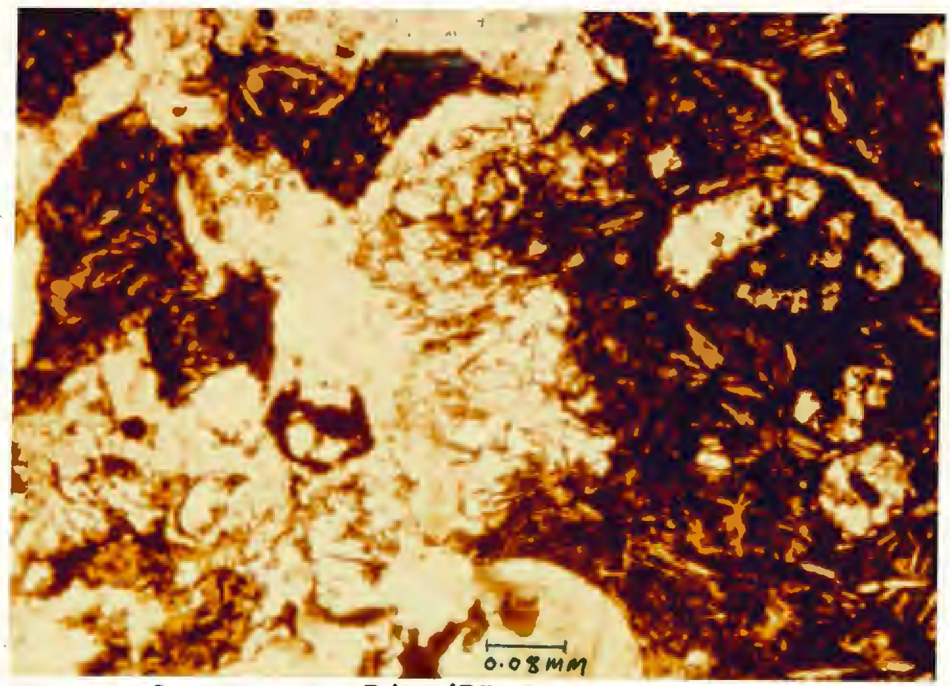

Figure 9. Sample 7/18/75-6 Photomicrograph of a lava from the hyaloclastite deposit of the Rio Loco Formation. White patches are calcite in amygdules and matrix. Plain light.

approximately 50^{o}. Plagioclase composition could not be determined due to the fine grain size and the advanced degree of weathering. Modal analyses of three samples are given in Table 1.

The abundance of amygdules in the lavas and the presence of pillow structures may be used to estimate depth of deposition (Moore, 1965; Jones, 1969). No detailed observations of amygdule size and abundance were recorded in the field, and only one sample big enough to show the internal arrangement of the amygdules was obtained. It shows vesicles increasing in size toward the center of the pillow with a rim of about 4 centimeters where no vesicles were formed. The amygdules range in size from less than 1 to 5 millimeters with an average around 2 millimeters. Assuming that these lavas are similar in composition with those studied by Jones a possible depth of extrusion of about 300 meters can be inferred. A more detailed study of the unit may yield a more precise figure.

The lavas weather to a dark purple-brown soil which in some cases reteins the original texture of the rock.

<u>The volcaniclastic breccias and conglomerates</u>(Fisher, 1961) are massive, polymictic, and unsorted with angular to subrounded fragments ranging in size up to 10 centimeters. The clasts range in composition from amygdular basic lava to hornblende and pyroxene porphyry. The fragments make up about 50 percent of the outcrops and

in most cases they are parabreccias and paraconglomerates, as the larger clasts do not touch each other. The matrix is clay- to sand-sized and is made up mainly of rok and crystal fragments ranging in size from less than 0.5 to 2.0 millimeters with a dominant size from 0.5 to 1 millimeter. The rock fragments can make up to 50 percent of the matrix and like the larger clasts they are mostly mafic lavas, pyroxene porphyry, hornblende porphyry and siltstone. Minor fragment of vesicular glass and devitrified glass are also present. Some of the rock fragments show alteration to chlorite, calcite, and epidote or a combination of these.

The crystal fragments are angular to subangular and constitute as much as 40 percent of the matrix. They are mainly augite and plagioclase and minor amounts of quartz, hornblende and opaque minerals. Minor amounts of fossils are also present. The euhedral to anhedral augite crystals are mainly unaltered but sometimes are replaced by chlorite and calcite; some are as long as 5 millimeters. The anhedral to euhedral plagioclase crystals are generally turbid and sericitized and some are zoned. The hornblende is euhedral to anhedral and some are completely replaced by epidote and chlorite. The quartz is commonly anhedral. Fine-grained clay constitutes up to 30 percent of the matrix; it is very chloritic and in some samples contains some epidote.

Thin to medium-bedded calcareous volcaniclastic breccias, sandstones, and siltstones occur as small thin to medium interbeds between lava flows; they are exposed only on a small road about 1.4 kilometer southwest of the town of Castaner. The calcareous breccias are made up mainly of angular to rounded, unsorted calcareous and volcanic rock fragments, plagioclase, and minor volcanic quartz, and some augite, all bounded by a sparry calcite cement.

Limestone occurs as a lens about 5 meters long and 2 meters thick south of Cerro Santo Domingo in Barrio Bartolo. It is classified as a biomicrite (Folk,1962).

Stratigraphic and structural relationships

Neither the base nor the top of the Rio Loco Formation is exposed in the southwest quarter of the Monte Guilarte quadrangle. The unit is in fault contact with the Yauco Mudstone in the northeast and in the north central part of the area in Barrios Guayo and Bartolo, and in fault contact with the Maricao Basalt in the northwest part of the area in Barrios Bartolo and Indiera Alta. A small fault block of Rio Loco Formation is also found in Barrio Indiera Alta in contact with the Yauco Mudstone. As mentioned earlier, the attitudes within the formation are very erratic; a good example of this is found in the calcareous interbeds about 1.4 kilometer southwest of the town of Castaner where the attitudes clearly indicate some kind of disturbance. This could be due to an unexposed intrusive body or to an unmapped fault. Detailed mapping to the north of the area will probably shed more light on this problem.

Slodowski (1956) reported that the Rio Loco Formation had a depositional contact on serpentinites, and based on stratigraphic relationships north and northeast of the town of Yauco, concluded that the Rio Loco Formation is a tongue within the Yauco Mudstone. In the Mayaguez area (Mattson, 1960) the Rio Loco Formation occurs on the flanks of an anticline where it lies between the Mayaguez group and the Bermeja Complex, which is considered to be the basal complex of the island.

Source and environment of deposition

The abundance of volcanic and hypabyssal rock fragments in the breccias and conglomerates strongly indicates a volcanic source for the volcaniclastic rocks. The lack similarities between the volcaniclastic fragments and the lava flows suggests that the interbedded lavas were not the main source. The source of the sediments must have been previously consolidated rocks. The lack of pyroclastic material indicates that explosive volcanic activity was not very important during the time of deposition. The calcareous sediments must have been deposited during periods when the volcaniclastic influx ceased.

The pillow structures, the hyaloclastite character of the lavas, and the interbedded sedimentary rocks indicate a submarine environment for the deposition of the unit. Slodowski (1956) and Mattson (1960) suggested a similar environment of deposition. However, Mattson (1960) also concluded, on the lack of pillows, that part of the unit was deposited subaerially.

MARICAO BASALT

The Maricao Basalt was originally named by Mattson (1960) for rocks exposed on the Rio Maricao, north of the town of Maricao along road 357, about 15 kilometers northwest of the Monte Guilarte quadrangle. His description of the formation is as follows:

> "Basalt porphyry is the most common type, occuring as flows and as fragments in breccias. Breccias and tuffs are also present but the main body of the lenses is made up of flows and flow breccias." (Mattson, 1960a, p.46).

In northwestern Puerto Rico the unit consists of thick-bedded to massive, coarse, basaltic tuffs (McIntyre, Aaron, and Tobisch, 1970). In the Maricao quadrangle, immediately to the west of the Monte Guilarte quadrangle, the Maricao Basalt consists of tuff breccias, thick-bedded coarse tuffs, and minor lava flows characterized by clinopyroxene phenocrysts.

The name "Basalt" is very misleading since the bulk of the formation in southwestern and northwestern Puerto Rico consists of breccias and tuffs and only minor lava flows. However, a more detailed regional study of the unit is necessary before redefining it.

The Maricao Basalt covers about 30 percent of the southwest quarter of the Monte Guilarte quadrangle and occurs mainly in Barrios Rubias, Naranjo, Aguas Blancas, and Rio Prieto, and in three small fault blocks in the northwest part of the area, in the northern part of Barrio Indiera Alta(Figure 5; Plate 1).

No fossils were obtained from the unit, but Mattson (1960) indicated that the Maricao Basalt interfingered with the Yauco Mudstone. If this is correct, then the age of the unit should be approximately Campanian to Maestrichtian (Upper Cretaceous).

The massive character of the units makes an estimation of thickness difficult. In the southwest quarter of the Monte Guilarte quadrangle, the total thickness of the unit cannot be determined since the unit has been faulted and intruded and its base is not exposed, but a minimum thickness of 1,300 meters is present in the mapped area. In the Central La Plata quadrangle, in northwestern Puerto Rico, the Maricao Basalt is at least 1,400 meters in thickness (McIntyre, Aaron, and Tobisch, 1970).

Rock descriptions

In the southwest quarter of the Monte Guilarte quadrangle, the Maricao Basalt consists mainly of massive, augite-rich, volcaniclastic breccias, conglomerates, and sandstones; subordinate calcareous sandstones and siltstones with minor claystones; and minor basaltic lava flows and limestones. A very striking characteristic is the abundance of augite crystals, both in the volcanic clasts and the sandy matrix of the breccias, and in the volcaniclastic sandstones. The unit is massive and bedding is visible only in the thin-to medium-bedded calcareous sedimentary rocks which appear to occur as lenses within the unit; their lateral extent could not be mapped due to their size and the degree of weathering in the area. These sediments occur in two main lenses; one is located about 600 meters northwest of Hacienda Las Piñas in Barrio Rubias; the other occurs about 500 meters east of Hacienda Santa Clara in Barrio Rio Prieto. Some of the calcareous rocks show signs of soft-sediment deformation, such as slump folds, slides in incompetent beds and chaotic masses of sediments (Figure 10).

The volcaniclastic parabreccias and paraconglomerates (Fisher, 1961) make up about 85 percent of the volume of the unit (Figure 11). They are dark grayish-green to light purple when fresh, massive, and polymictic, with angular to subrounded clasts. The clasts constitute up to 75 percent of the rock in the individual outcrops, with an average of 50 percent. In most cases these rocks are parabreccias and paraconglomerates as the larger clasts do not touch each other. They range in character from pyroxene porphyry to augite-rich phaneritic (plagioclase composition indeterminable) rock fragments to basaltic amygdular rock fragments. Some minor calcareous rock fragments and rudist fragments are present locally. All of the clasts range in size up to 30 centimeters with an average size of about 15 centimeters. No sorting is evident.

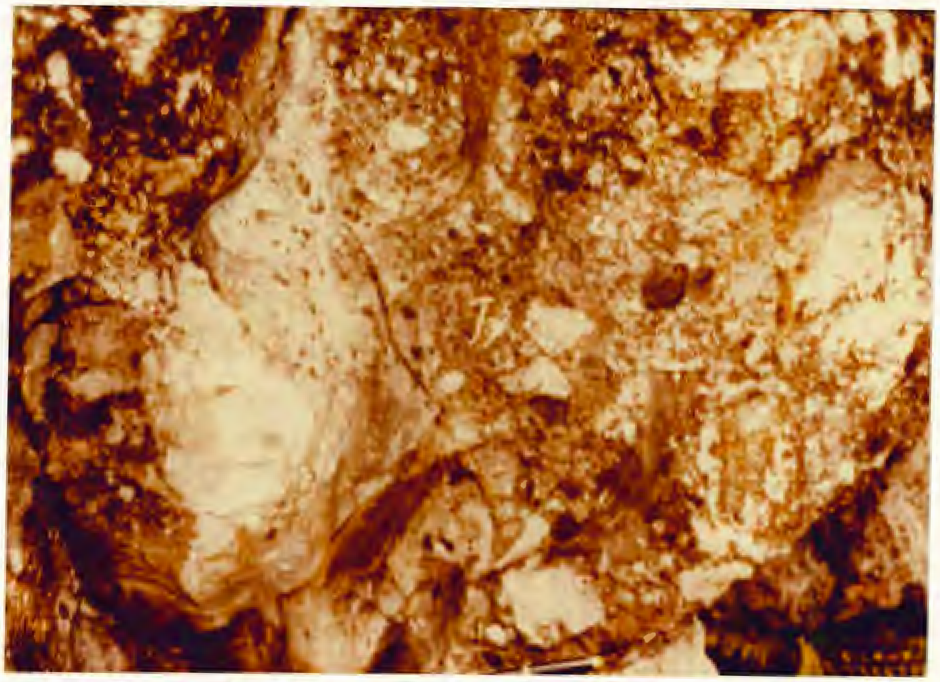

Figure 10. Chaotic block of calcareous sedimentary rock in the Maricao Basalt on road 374 about 200 meters south of Hacienda Santa Maria between Barrio Rubias and Barrio Indiera Alta. Pen is 13 centimeters long.

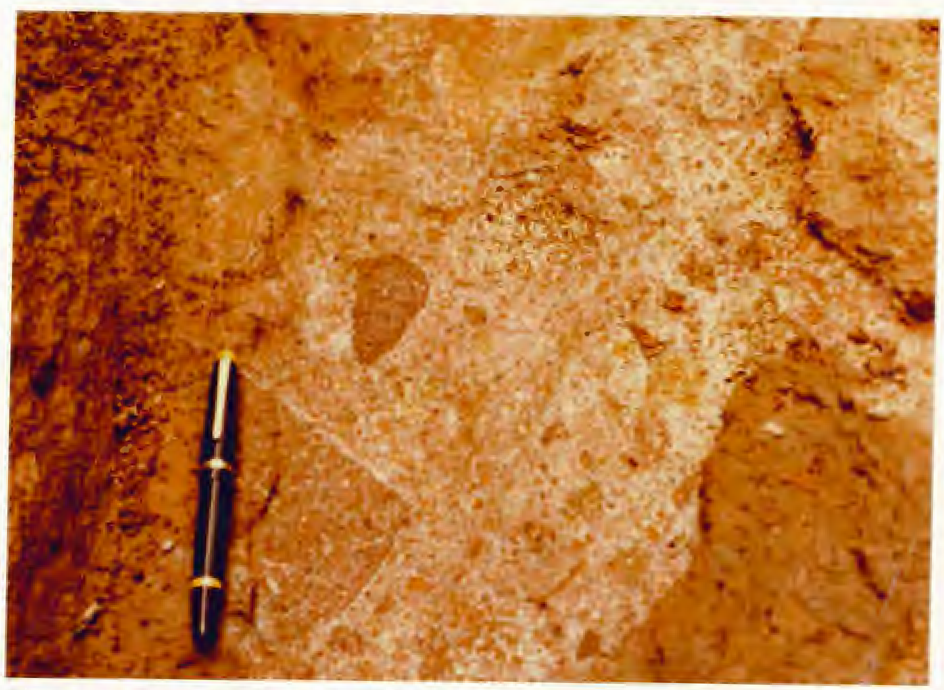

Figure 11. Volcaniclastic breccia of the Maricao Basalt in a ditch on a small road about 400 meters east of Hacienda La Juanita in Barrio Rio Prieto. Note that exposure has been highly weathered to a saprolite but yet displays the original texture. Pen is 13 centimeters long.

The matrix of the parabreccias and paraconglomerates is mud- to sand-size and is made up mainly of volcaniclastic rock and crystal fragments with an average size of about 0.5 millimeters. Rock fragments constitute up to about 60 percent of the matrix and are mainly gabbroic, augite porphyry, plagioclase porphyry, augite-plagioclase porphyry with pilotaxitic groundmass, and minor hornblende porphyry, quartz-plagioclase porphyry rock fragments, and minor glass and pumice fragments (Figures 12 and 13; Table 2). Some of the rock fragments have been completely altered to chlorite, calcite, and epidote or a combination of these. Some of the augite porphyry and hornblende porphyry rock fragments are similar in texture to the augite porphyry and hornblende porphyry intrusive rocks in the map area and some are finer-grained. The angular tosubrounded crystal fragments, which in some samples constitute up to about 40 percent of the matrix, are mainly augite and plagioclase. Minor opaques, fossils, and devitrified glass are also present. The euhedral to anhedral augite crystals are mainly unaltered but in places are replaced by chlorite and calcite. The euhedral to anhedral plagioclase crystals are mainly turbid and serecitized and some are zoned. The hornblende is euhedral to anhedral ad is locally completely replaced by epidote and chlorite. The quartz grains are typically anhedral. The finer matrix between

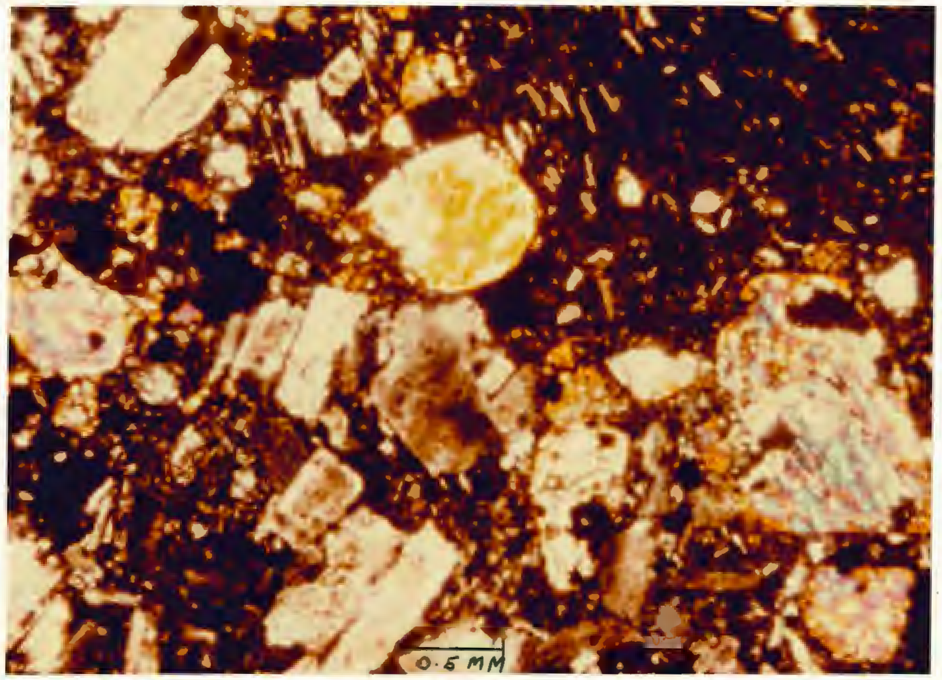

Figure 12. Sample 7/14/75-1 Sandy matrix of a volcaniclastic breccia in the Maricao Basalt. It consist mainly of augite porphyry, plagioclase porphyry rock fragments and augite and plagioclase crystals. Crossed nicols.

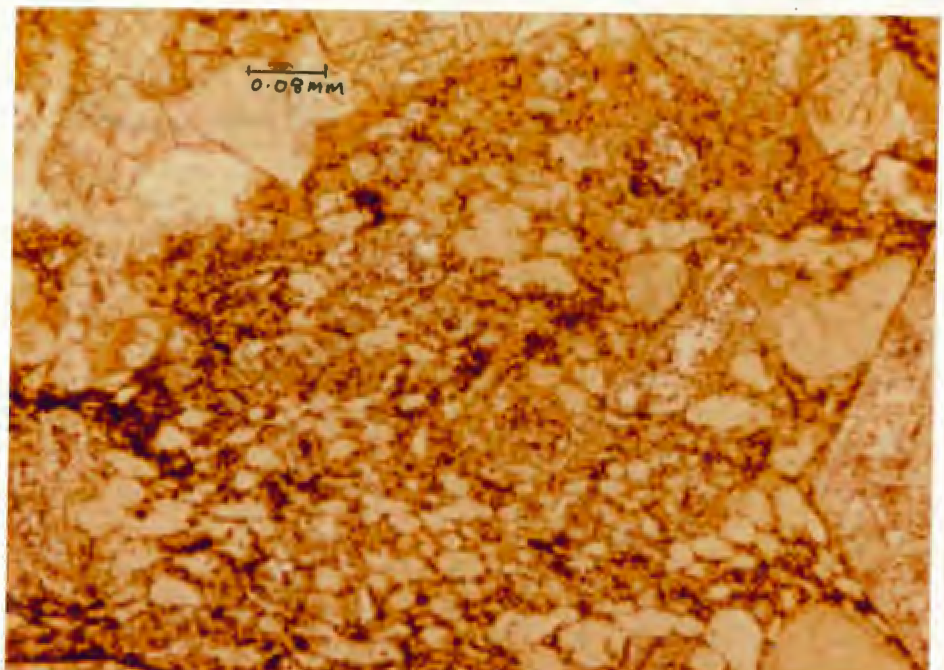

Figure 13. Sample 8/1/75-4 Pumice fragment in matrix of a Maricao Basalt volcaniclastic breccia. Fragment is completely zeolitized and vesicles are filled with zeolite minerals. Plain light.

Table 2.

MODAL ANLYSES OF THE VOLCANICLASTIC ROCKS OF THE MARICAO BASALT

	7/8/75-6	7/14/75-1	7/30/75-1	8/19/75-2
Framework Grains				
Minerals				
Plagioclase	14.1	10.6	2.0	8.8
Augite	2.1	11.5	18.3	9.6
Hornblende	1.0	-	2.7	-
Quartz	1.4	-	-	-
Opaques	tr	5.0	2.3	5.0
Total mineral grains	18.9	27.1	25.3	23.4
Rock fragments				
Volcanic-hypabyssal				
Augite porph.	6.0	-	19.7	0.8
Plag. porph.	5.5	5.5	4.1	2.6
Hornblende porph.	1.4	-	5.1	0.8
Augite-plag. porph.	-	11.1	2.1	15.0
Plag. porph. oxidized	-	2.3	1.1	1.1
Augite porph. oxidized	7.0	-	2.1	14.5
Augite porph. amygd.	-	-	5.8	-
Hornbl.-augite porph.	-	-	-	tr
Pilotaxitic frag.	2.2	4.1	-	tr
Plag.-rich frag.	5.5	1.3	0.4	0.8
Augite-qtz-plag porph.	-	6.0	-	-
Other rock fragments				
Gabbroic frag.	-	22.2	-	-
Altered frag.	4.7	0.4	10.2	0.8
Silt frag.	4.4	-	-	-
Fossils	2.6	-	-	-
Total rock fragments	38.4	50.9	50.6	36.4
Matrix-cement				
calcite	14.0	2.0	6.6	-
chlorite	28.8	19.4	12.5	-
quartz	-	-	6.0	-
hematite	-	-	-	39.2
	100.0	99.4	99.0	98.6

7/8/75-6 Sandstone of the Maricao Basalt from an outcrop on a small road 0.5 kilometer northeast of Hacienda La Juanita in Barrio Rio Prieto.

7/14/75-1 Sandstone of the Maricao Basalt from outcrops at Hacienda Santa Teresa in Barrio Rio Prieto.

7/30/75-1 Sandtone of the Maricao Basalt from a small road 0.8 kilometer northeast of Hacienda Santa Clara in Barrio Rio Prieto.

8/19/75-2 Matrix of parabreccia of the Maricao Basalt from an outcrop 0.8 kilometer southeast of Hacienda Leonor in Barrio Aguas Blancas.

the sand grains is a very fine-grained chloriti material which constitutes as much as 40 percent of the matrix. At some localities quartz and calcite cements are present. At one locality the matrix is highly oxidized.

The volcaniclastic sandstones are light to dark gray to light to dark brown, when fresh, and are massive, unsorted and pyroxene-rich. The grains are made up mainly of angular to subrounded volcaniclastic rock and crystal fragments, ranging in size from less than 0.25 up to 4.0 millimeters, with an average size of about 1.0 millimeter. The rock fragments, which constitute up to 60 percent of the rock, consist mainly of plagioclase porphyry, augite porphyry, quartz-plagioclase volcanic porphyry, and hornblende porphyry rock fragments, some of which show alteration to chlorite and calcite. Some calcareous rock fragments are also present. The crystal fragments, which are angular to subrounded and can make up to 30 percent of the rock, are mainly plagioclase, augite with minor hornblende, quartz and opaques. Minor fossils can be present.

The plagioclase crystals, which are euhedral to anhedral, are usually turbid and sericitized, most are twinned and some are zoned. The augite crystals, which are fairly fresh, are euhedral to anhedral, but can show alteration to chlorite and calcite. The quartz is usually anhedral. The hornblende crystals, which are euhedral to subhedral, can be altered to chlorite and calcite (Figure 14 and 15, Table 2).

A fine-grained chloritic matrix makes up to about 15 percent of the rock. In some localities calcite cement is present in the matrix.

Calcareous volcaniclastic sandstones and siltstones (Fisher, 1961) with minor claystones occur as small lenses within the unit. They are dark to light brown, thin- to medium-bedded, and are poorly sorted. The grains in the sandstones are made up mainly of volcaniclastic rock and crystal fragments with an average size of about 0.5 to 1.0 millimeter. The rock fragments, which can be rounded to subangular and constitute up to 60 percent of the rock, are made up mainly of calcareous rock, augite porphyry and plagioclase porphyry, with minor plagioclase-rich fragments with a pilotaxitic texture. Some of the rock fragments show alteration to chlorite and calcite. The crystal fragments, which can constitute up to 30 percent of the rock and are angular to subrounded, are mainly plagioclase, quartz, and augite; minor fossils and opaques are also present.

The plagioclase crystals, which are euhedral to subhedral, are usually turbid and sericitized and some are twinned and occasionally zoned. The augite crystals are euhedral to anhedral and show alteration to chlorite and calcite. Quartz is usually anhedral but in some samples euhedral crystals are present.

The matrix is made up mainly of a dark brown calcareous clay, and can make up to 30 percent of the rock. In some cases calcite cement is present.

The siltstones are made up mainly of silt-sized angular fragments of quartz, plagioclase, augite, and fossils, all in a dark brown calcareous matrix. The light brown claystones are made up mainly of dark brown calcareous clay.

A basaltic lava flow occurs within the volcaniclastic breccias and conglomerates and makes up less than 1 percent of the volume of the unit in the mapped area. The flow crops out in a small area about 1 kilometer south of Hacienda Resurreccion and about 600 meters west of Quebrada Grande in Barrio Naranjo. It has been traced over a strike length of about 0.5 kilometer.

The lava flow is light to dark gray to dark purplish-gray when fresh, fine- to medium-grained to aphanitic, amygdular, and porphyritic, it is probably basaltic in composition. It is made of about 50 to 70 percent phenocrysts of plagioclase and augite in a fine-grained groundmass. The euhedral to anhedral augite crystals are as much as 2.5 millimeters in length and constitute as much as 25 percent of the rock, but typically never exceeds 15 percent. Many augite crystals are

Table 3.

MODAL ANALYSES OF THE MARICAO BASALT LAVA FLOW

	7/3/75-10	7/4/75-2
Phenocrysts		
Plagioclase	25.5	22.1
Augite	14.5	10.0
Opaques	0.3	0.9
Groundmass	59.4	67.0
	99.7	100.0
Percent of amygdules in the rock.	10	10

7/3/75-10 Basaltic lava flow from the Maricao Basalt from outcrops about 1 kilometer south of Hacienda Resurreccion in Barrio Naranjo.

7/4/75-2 Basaltic lava flow from the same locality as sample 7/3/75-10.

poikilitic, enclosing grains of magnetite. They show alteration to calcite, chlorite, and epidote, and an unidentified light yellowish-brown alteration product. The plagioclase phenocrysts are euhedral to subhedral and as much as 3.0 millimeters long; they are usually twinned, following albite and pericline laws. They show some alteration to chlorite, calcite, and sericite. The plagioclase makes up abut 75 percent of the rock. the opaque minerals are typically magnatite and minor pyrite and constitute 5 percent of the rock. Plagioclase composition was not determined optically due to the degree of weathering.

The aphanitic groundmass consists of plagioclase, augite, and minor oxidized glass (?). The texture are dominantly pilotaxitic. The amygdules form from 10 to 15 percent of the rock and are commonly calcite, chlorite, hematite, quartz, or zeolite (Table 3).

Limestone occurs as a small lens about 10 meters in length, about 250 meters southwest of Hacienda La Juanita between Barrios Naranjo and Rio Prieto. It is massive and is weathering out as big boulders. The limestone is made up of about 50 percent fossils, 20 percent carbonate intraclasts and about 30 percent sparry cement. This rock is mainly a biointrasparrite (Folk, 1962).

Stratigraphic and structural relationships

The Maricao Basalt seems to be underlying the Yauco Mudstone unconformably; however, this relationship was only seen in one place, on a small road southeast of Monte Membrillo. Here the Yauco Mudstone is dipping to the south and the contact is sharp, elsewhere the contac is buried beneath thick soil cover. The base of the unit is not exposed in the map area due to intrusions and faulting. The calcareous sedimentary rocks in the unit provide the only bedding attitudes. According to these attitudes the contact between the Maricao Basalt and the Yauco Mudstone is discordant and is probably an angular unconformity. This is noticed in the fault block est of the Monte Membrillo fault in Barrio Rio Prieto. In the fault block west of this fault the contact was crossed various times but it was never seen due to the thick soil cover. In the Mayaguez area, to the west of the Monte Guilarte quadrangle, the Maricao Basalt occurs "above and as lenses in the Yauco Mudstone" (Mattson, 1960a, p.46). McIntyre (1973, p.8), in his report on the Maricao quadrangle, indicated that the Maricao Basalt is "a tongue-like unit within the Yauco Mudstone". In the Central La Plata quadrangle, in west-central Puerto Rico, the Maricao Basalt overlies the Yauco Mudstone concordantly and probably conformably (McIntyre, Aaron, and Tobisch, 1970). Apparently the Maricao Basalt is a lithofacies which does not occupy a single stratigraphic horizon. Complex intertonguing of the various units occur at several localities (Mattson, 1960; Krushensky and Monroe, 1975) and the sequence found at a given locality cannot be carried elsewhere in the region.

Igneous bodies intrude the unit in several places but no metamorphic effects were not noticed. The only visible effect is the tilting of the calcareous sediment beds adjacent to the intrusive bodies.

Source and environment of deposition

The abundance of volcanic, hypabyssal, and plutonic rock fragments and crystal fragments indicate an igneous source. The almost complete absence of definite pyroclastic material within the unit suggests that there was no appreciable volcanic activity other than minor flows, occurring during the deposition of the Maricao Basalt and that the material seems to have been derived from pre-existing rocks. The great variety of volcanic and other rock fragments is further evidence of an epiclastic rather than a pyroclastic origin. The angularity of most of the clasts and the abundance of unstable crystal fragments strongly indicates that the material was worked only enough to cause some sand grains and coarser fragments to become subrounded. The mode of transportation of this material to the basin of deposition must have had only a minor effect on the rounding and sorting of the fragments. This could have been accomplished by means of massive "mudflows" possibly triggered by tropical rains in a tectonically unstable environment. This mechanis is especially appealing in light of the poorly sorted nature of the parabreccias and paraconglomerates in which the larger clasts commonly are separated by abundant finer matrix. This process will give rise to rapid erosion, transportation and burial with little opportunity for reworking. Every now and then, the influx of volcaniclastic material to the basin decreased and in some cases ceased, and calcareous sediments and limestone lenses were formed.

Mattson(1960) in his report of the Mayaguez area, suggested that the depositional environment of the Mayaguez group, which includes the Maricao Basalt, was a tropical shallow marine area with nearby volcanic activity and with some older rocks exposed above sea level. Apparently the Maricao Basalt in the southwest quarter of the Monte Guilarte quadrangle was formed mainly from the erosion of the older rocks which were above sea level and producing a great volume of epiclastic material. Part of this material was deposited on land, for the lava flow within the formation is not pillowed. The calcareous sediments are evidence for marine deposition for part of this unit. Both the source area and the depocenters were probably tectonically unstable.

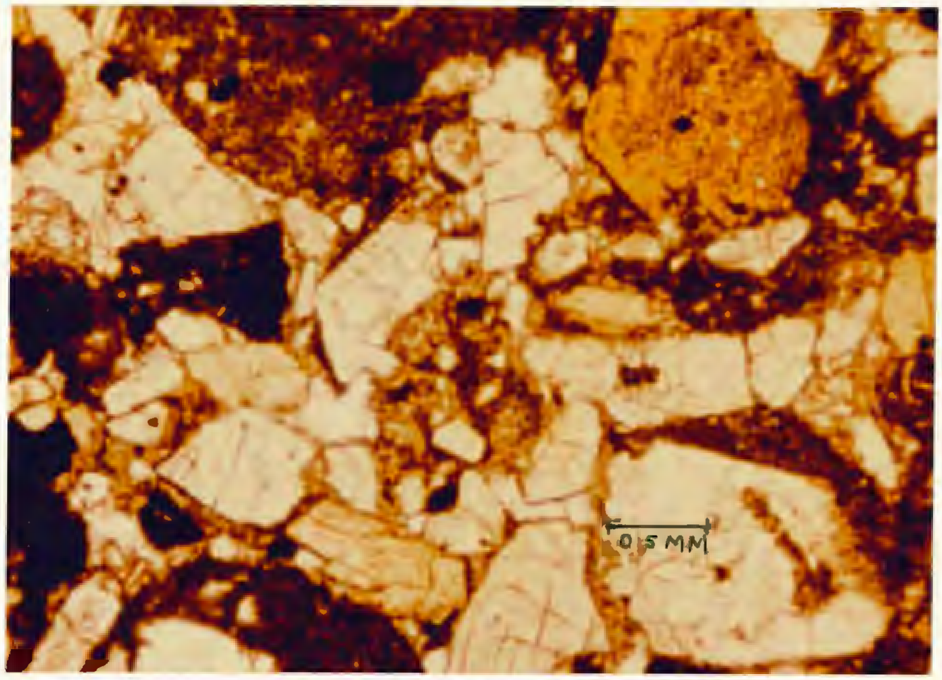

Figure 14. Sample 7/30/75-1 Volcaniclastic sandstone in the Maricao Basalt. It consist mainly of augite and plagioclase porphyry rock fragments, and plagioclase and augite crystal fragments. Most of the matrix is a dark brown calcareous clay. Plain light.

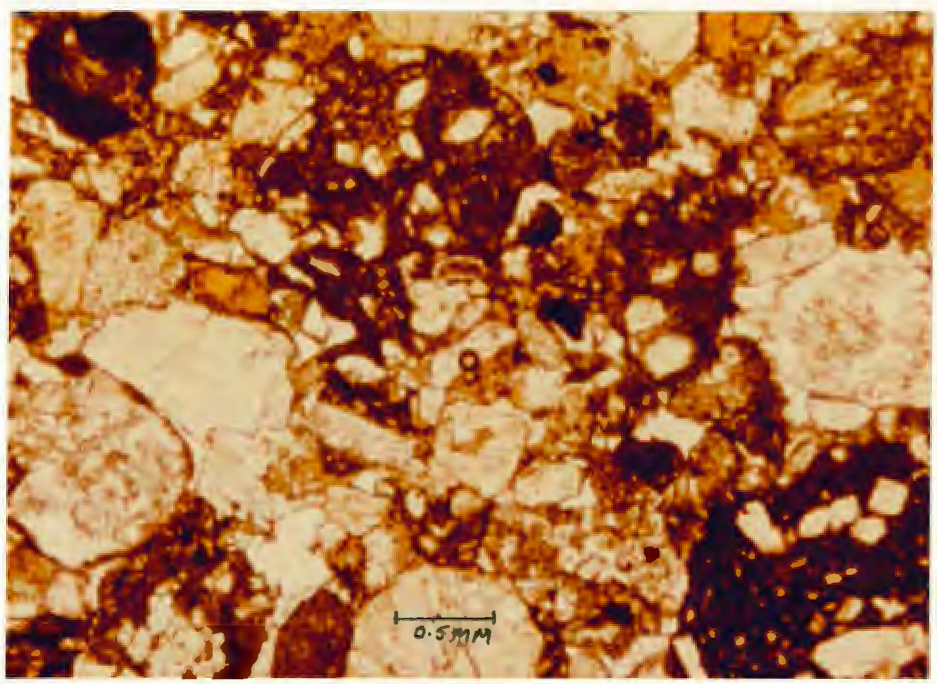

Figure 15. Sample 7/24/75-1 Volcaniclastic sandstone in the Maricao Basalt. It is composed mainly of plagioclase and augite porphyry rock fragments and plagioclase and augite crystal fragments in a chloritic matrix. Plain light.

YAUCO MUDSTONE

The formation was originally named the Rio Yauco Shales by Mitchell (1922) for rocks which are exposed along the Rio Yauco, east of the Monte Guilarte quadrangle. Slodowski (1956) replaced the term "shale" with the term "formation" because of the lack of fissility in the rocks. Mattson (1960) redefined the formation and called it the Yauco Mudstone.

This formation is one of the most extensive units in southwestern Puerto Rico, extending from the Ponce quadrangle in the south (Krushensky and Monroe, 1975) to the Rincon quadrangle in the westernmost tip of the island (McIntyre, Aaron, and Tobisch, 1970), an area of about 80 by 20 kilometers (Figure 3).

The Yauco Mudstone covers about 20 percent of the southwest quarter of the Monte Guilarte quadrangle, occurring in six different fault blocks.

Four samples collected from the formation contained Foraminifera. They were identified by Charles C. Smith of the U. S. Geological Survey (written communication, January, 1976), as follows:

(1) Lithology: Limestone (7/16/75-2)

Fauna: Globigerinelloides sp. indet.
?Heterohelix sp.

Age: Coniacian through Late Maestrichtian

(2) Lithlogy: Calcareous Siltstone (7/22/75-1)

Fauna: Heterohelix sp. indet.
Globigerinelloides sp. indet.
Globotruncana sp. cf. elevata (Brotzen)
miliolid benthonic foraminifera

Age: The questionable presence of Globotruncana elevata indicates this sample to be middle Campanian to late Maestrichtian in age.

(3) Lithology: Limestone (8/7/75-1)

Fauna:

Pseudotextularia elegans (Rzehak)	VA
Globigerinelloides sp. indet.	VA
Globotruncana aegyptiaca Nakkady	C
Globotruncana bulloides (Vogler)	R
Globotruncana contusa (Cushman)	A
Globotruncana elevata (Brotzen)	VA
Globotruncana gansseri Bolli	C
Globotruncana linneiana (d'Orbigny)	R
Globotruncana staurtiformis Dalbiez	C
Rugoglobigerina macrocephala Bronnimann	R
Rugoglobigerina rugosa (Plummer)	A

Key: VA more than 10
A 6-10
C 3-5
R 1-2

Age: Middle Maestrichtian

(4) Lithology: Limestone (8/24/75-1)

Fauna: Nummulites sp. (rare)
?Rugoglobigerina rugosa (Plummer)
benthonic milioid foraminifera

Age: Questionably early Campanian through late Maestrichtian.

Slodowski (1956) assigned a Santonian or basal Campanian to Maestrichtian (Upper Cretaceous) age to the formation based on Foraminifera. Mattson (1960) reported a Campanian to Maestrichtian age but noted it could possibly be as old as Turonian. McIntyre, Aaron, and Tobisch (1970) assigned a Campanian to Maestrichtian age, also based on Foraminifera. Thus, based on the paleontologic data presented here and the previous work, the age of the Yauco Mudstone is Campanian to Maestrichtian, but possibly in part as old as Turonian.

In the southwest quarter of the Monte Guilarte quadrangle the total thickness of the Yauco Mudstone cannot be determined since the unit is faulted and the top of the unit is not exposed. A minimum thickness of about 360 meters was measured in the fault block west of Barrio Rubias. Slodowski (1956) calculated a thickness for the unit of 1,500 meters in the Yauco area. Mattson (1960) calculated a thickness for the unit of about 2,400 to 2,800 meters in the Mayaguez area. McIntyre, Aaron, and Tobisch (1970) reported a minimum thickness of 500 meters but mentioned that small scale folding is present and little confidence can be placed in this figure.

Rock descriptions

The Yauco Mudstone consists of hard, calcareous, volcaniclastic sandstones and siltstones; non-fissile claystones, limestones, minor calcareous conglomerates and breccias, and tuffs. The rocks range in color from dark bluish-gray to dark gray when fresh. A prominent characteristic is the conspicuous and persistent thin- to medium-bedding, with an average thickness of 5 to 10 centimeters, ranging locally to massive (Figure 16). Massive bedding is apparently more abundant in the northwest and west-central part of the area in Barrio Indiera Alta. Stratification is expressed in color banding which is due to variation in grain size and composition. Fine-grained material makes up the thin beds, and the coarser-grained material makes up the thicker beds. The sandstones are crudely graded and small scale primary deformation structures are common. These include load casts, slump folds, and small slides in incompetent beds (Figure 17). Scour and fill structures are also present, and small scale cross-beds were noticed but were not common. No paleocurrents measurements were taken. All of these structures are well exposed along road 128, in the western part of Barrio Rubias. Some of the cross-bedded sandstones contain flaser bedding with clay wisp up to 1 centimeter in length (Reinech and Singh, 1973).

The unit contains abundant microfossils, mainly in the limestones and in the calcareous siltstone. Locally, in some of the calcareous conglomerates and breccias, rudist fragments are present. Well preserved trace fossils were found in Rio Chiquito, in the southwest corner of the area in Barrio Rubias (Figure 18). They are about 4 centimeters in width with some internal structure and they show a random grazing pattern (Seilacher, 1964).

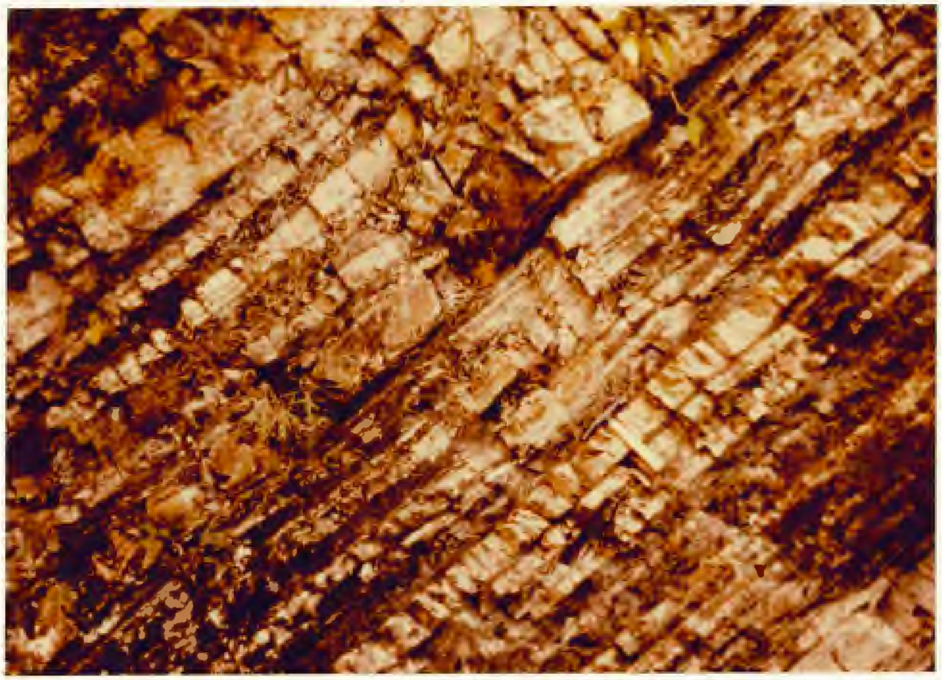

Figure 16. Thin- to medium-bedded Yauco Mudstone on road 128 in the southwest corner of the area in Barrio Rubias. Hammer is 25 centimeters long.

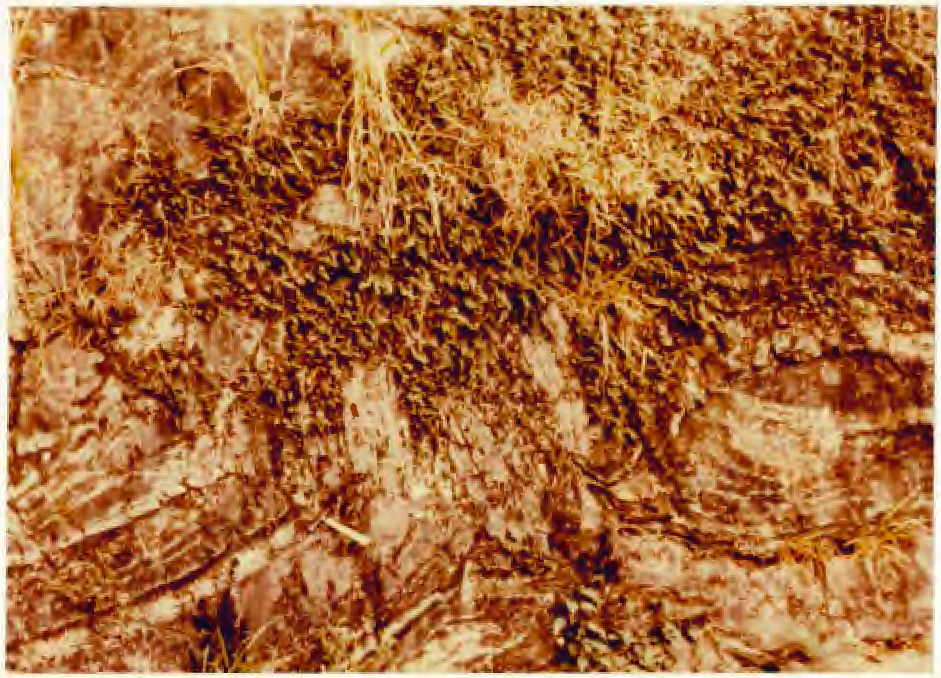

Figure 17. Soft sediment deformation in the Yauco Mudstone on road 128 in the southwest corner of the area in Barrio Rubias, See hammer in lower center (25 centimeters long) for scale.

Figure 18. Trace fossils in the Yauco Mudstone in Rio Chiquito in the southwest corner of the area in Barrio Rubias. Hammer handle 4 centometers wide.

The Yauco Mudstone weathers to a light orange-brown saprolitic soil which in most cases retains the original textures of the rocks. The sandstones and the coarse-grained siltstone weather positively in the outcrops while the claystone weather negatively. The claystones and the fine-grained siltstones weather into short, tabular, pencil-like fragments with conchoidal fracture.

The calcareous volcaniclastic sanstones (Fisher, 1961) make up the thicker beds, have the least amount of calcareous material and exibit almost no signs of soft sediment deformation. Graded bedding is best observed in these sandstones. Slodowski (1956) reported, after studying the Yauco Mudstone in four quadrangles, that the "volcanic wackes" form a small percentage of the volume of the unit. In the mapped area this does not appear to be the case; in fact, the sandstones represent a significant part of the volume of the unit in the southwest quarter of the Monte Guilarte quadrangle.

The sandstones are light to dark gray to light brownish-gray, poorly sorted, with angular to subrounded rock and crystal fragments in a dark brown calcareous, clayey matrix. Most of the rock and crystal fragments range from less than 0.5 to 3 millimeters in diameter ; the average size is about 1 millimeter. The rock fragments make up from 20 to

70 percent of the sandstones, and mainly consist of limestones, siltstones, mafic igneous rocks, plagioclase-rich volcanic rock, augite porphyry, hornblende porphyry and quartz-rich volcanic rock (Figure 19 and 20, Table 4). Some of the rock fragments have been completely altered to chlorite, calcite, and epidote, and some quartz or a combination of these. A sample from a small trail about 0.8 kilometer south of Hacienda Arbela contains some rock fragments which, with a potassium cobaltinitrite stainning procedure, stained yellow indicating that they are potassic in composition. However, the potassium feldspars could not be distinguished in thin section. The crystal fragments are mainly plagioclase and augite with minor hornblende, opaques and quartz, although quartz is abundant at some localities. Minor fossils and devitrified glass fragments are also present. The plagioclase crystals are euhedral to subhedral, some are zoned, and are mostly turbid and sericitized, although some fresh crystals are present. The aigite crystals are euhedral to anhedral and show alteration to chlorite and calcite. The hornblende, which is euhedral to anhedral, shows alteration to chlorite. The quartz is subhedral to anhedral and in some cases euhedral crystals are present.

The dark brown calcareous clayey matrix makes from 25 to 45 percent of the rock and authigenic chlorite and calcite are scattered through it.

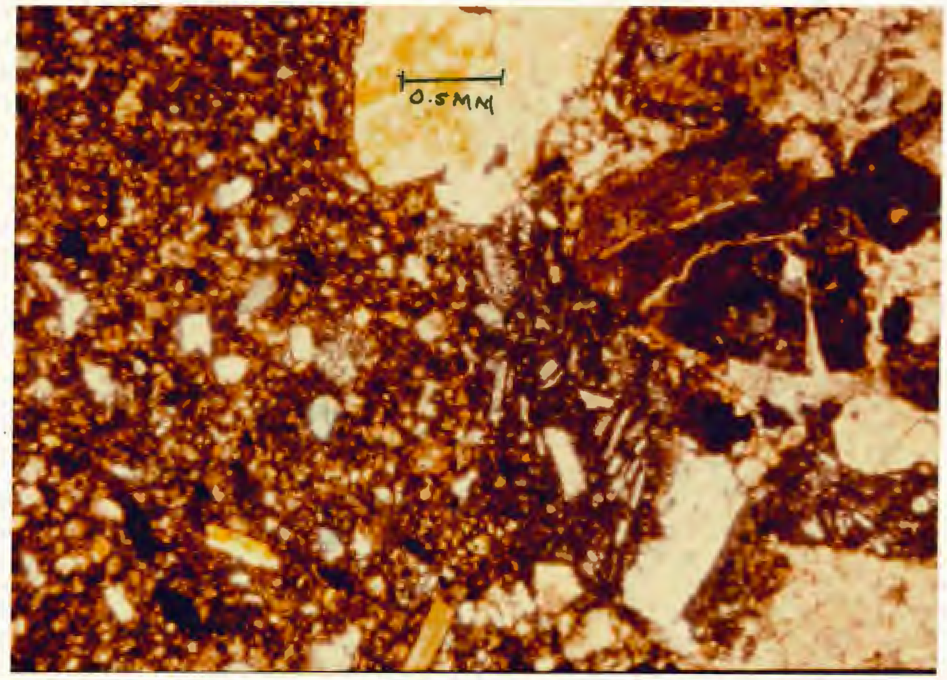

Figure 19. Sample 7/10/75-2 A calcareous volcaniclastic sediment of the Yauco Mudstone. Original bedding is vertical in photograph. To the right a sandstone bed made of mafic rock fragments and augite crystals in a calcareous clayey matrix. To the left a silt bed made of plagioclase, augite, hornblende, and quartz. Crossed nicols.

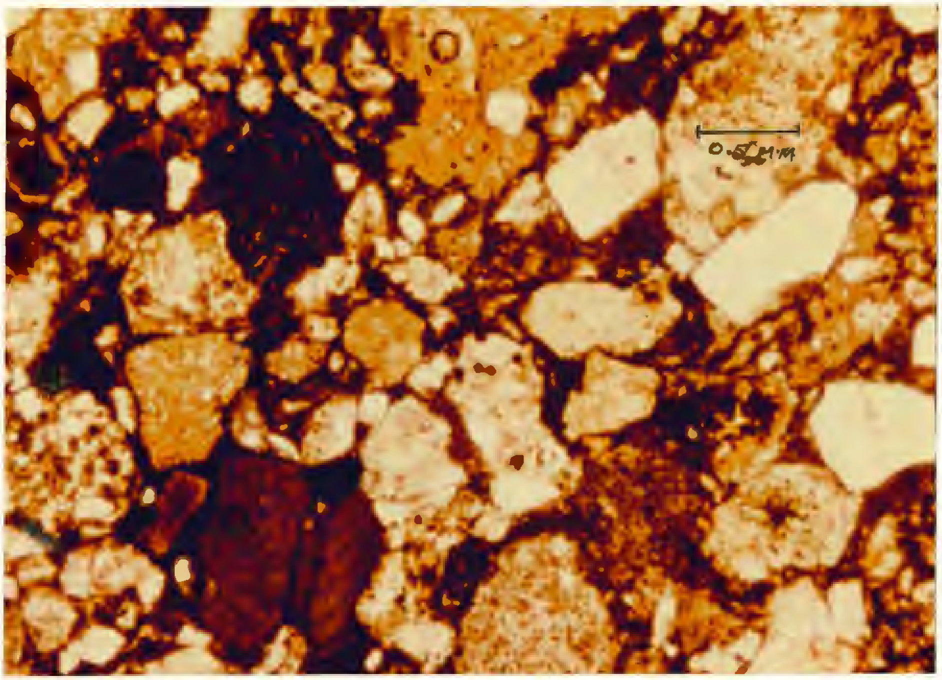

Figure 20. Sample 7/29/75-3 Volcaniclastic sandstone of the Yauco Mudstone made up of plagioclase porphyry, mafic volcanic rock, and augite porphyry rock fragments, and plagioclase and augite crystals in a calcareous matrix. Some fossils are present. Plain light.

Figure 21. Calcareous breccia in the Yauco Mudstone on road 128, 1.4 kilometer north of the intersection with road 428 in Barrio Indiera Alta. Pen is 13 centimeters long.

Table 4.
MODAL ANALYSES OF THE VOLCANICLASTIC ROCKS OF THE YAUCO MUDSTONE

	7/23/75-3	7/24/75-3	7/29/75-3	7/30/75-2	8/24/75-3
Framework Grains					
Minerals					
Plagioclase	6.7	12.3	15.0	3.6	16.4
Augite	-	3.7	0.2	11.7	2.6
Quartz	2.5	1.3	4.4	2.4	3.0
Hornblende	-	1.4	-	4.7	-
Opaques	-	1.1	2.7	0.4	0.6
Total minerals	9.2	19.8	22.3	22.8	22.6
Rock fragments					
Volc.-hypabyssal					
Plag. porph.	7.8	16.6	9.6	13.9	12.3
Augite porph.	22.4	2.8	-	10.5	2.3
Augite-plag. porph.	-	0.9	-	-	-
Quartz-plag. volc. frag.	0.5	-	-	-	-
Plag.-rich frag.	4.5	-	8.8	-	2.3
Hornblende porph.	10.0	0.9	0.2	3.0	-
Other rock fragments					
Calc. frag.	4.9	-	5.0	6.6	7.0
Chert frag.	0.9	-	5.8	0.5	0.4
Altered frag.	1.2	16.0	6.7	4.6	5.5
Glass frag.	-	-	1.4	2.4	-
Fossils	2.5	7.6	1.9	0.4	2.1
Total framework grains	54.7	44.8	39.4	41.9	31.9
Matrix-cement					
chlorite-epidote	-	-	-	-	37.4
calcite	35.6	34.3	36.4	34.8	7.7
	99.5	98.9	98.1	98.6	99.6

7/23/75-3 Sandstone of the Yauco Mudstone from outcrops in the Rio Prieto about 0.4 kilometer east of Hacienda San Lorenzo in Barrio Indiera Alta.

7/24/75-3 Sandstone of the Yauco Mudstone from outcrops on a small road 0.5 kilometer west of Hacienda Arbela in Barrio Rio Prieto.

7/29/75-3 Sandstone of the Yauco Mudstone from outcrops on a small trail 0.5 kilometer south of Hacienda Maria Antonia in Barrio Indiera Alta.

7/30/75-2 Sandstone of the Yauco Mudstone from outcrops 0.8 kilometer south of Hacienda Arbela in Barrio Rio Prieto.

8/24/75-3 Sandstone of the Yauco Mudstone from kilometer 20.9 on road 128 in the southwest corner of the area in Barrio Rubias.

Volcaniclastic siltstones and claystones make up the thin to medium beds of the formation, have sharp, even bedding planes and are very calcareous. They break with subconchoidal to conchoidal, smooth-surfaced fractures. These silty beds commonly contain small, dark brown mud chips. Microfossils are common and locally abundant. Most of the soft-sediment deformation within the formation occurs in these beds. The siltstones are made of angular fragments of plagioclase, quartz, pyroxene, fossils, chert, some hornblende and small rock fragments, and minor glauconite grains in an abundant light to dark brown calcareous clay matrix which comprises 20 to 80 percent of the rock (Figure 19). The claystones are made mainly of this brown calcareous clay. Laminations are due to variations in the relative amounts of matrix and silt-sized material.

Plagioclase, quartz, and pyroxene grains, and fossils make up from 15 to 70 percent of the rock and range in size from .06 to .03 millimeters. Authigenic calcite has partially replaced most of the plagioclase and pyroxene grains and is usually scattered throughout the matrix. Foraminifera tests are commonly recrystallized and filled with crystalline calcite and in some cases with opaques; they locally constitute up to 50 percent of the rock but are absent at other localities. Small amounts of fine-grained pyrite are disseminated throughout the siltstone and claystones. Some of the siltstone beds contain minor muddy lenses.

Calcareous conglomerate and breccia occur as sporadic lenses or beds. They are light to dark gray with angular to subrounded fragments, form thick beds, and commonly contain microfossils (Figure 21). The fragments range in color from light brown to light purple; the matrix is dark brown and very muddy. The clasts are mainly limestone fragments, making up to 75 percent of the rock; siltstone fragments and pyroxene and plagioclase-rich volcanic rock fragments are present in lesser amounts. Some fossils, chert, quartz, plagioclase, and pyroxene crystals are also present. The dark brown clayey, calcareous matrix has been locally replaced by authigenic calcite. The abundant limestone rock fragments are mainly biointrasparite and intrabiosparite (Folk, 1962).

The limestones are light to dark gray, dense, and thin- to medium-bedded. They are made up mainly of fossils and micritic matrix with minor carbonate pellets, quartz, plagioclase, pyrite, and some mafic volcanic rock fragments. Foraminifera tests make up from 25 to 50 percent of the rock, and angular to subangular quartz and plagioclase grains constitute up to 10 percent of the rock. The limestones are generally biomicrites (Folk, 1962) (Figure 22). Small lenses of darker material, probably carbon-rich and organic in origin, are locally present.

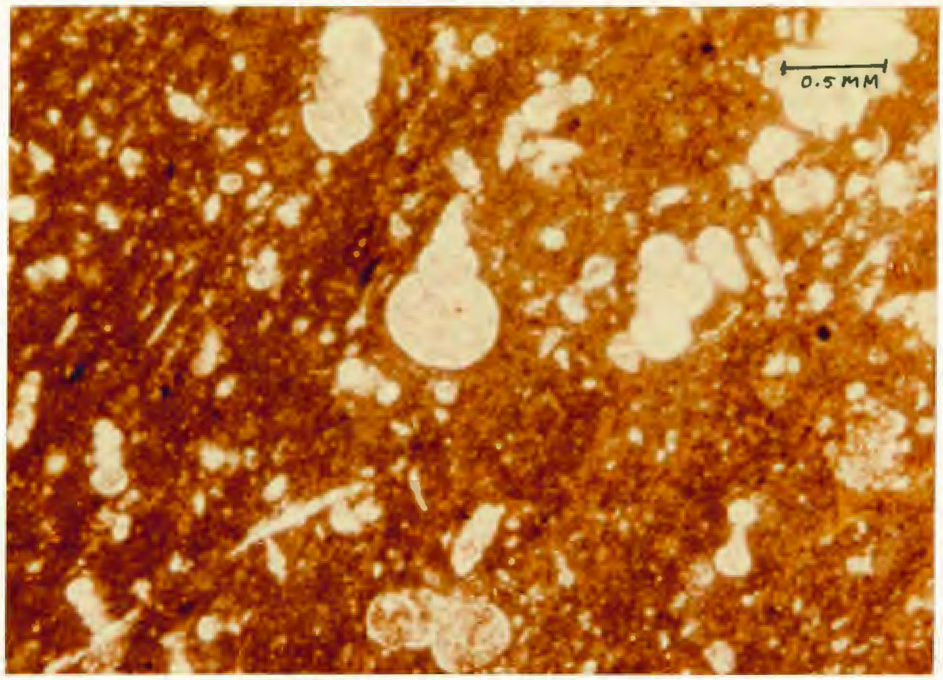

Figure 22. Sample 8/7/75-1 Biomicritic limestone of the Yauco Mudstone. Plain light.

Tuff beds constitute a minor rock type in this formation. Most of them have been completely weathered, but their textures have been preserved in the saprolitic soil. These textures indicate that they were originally crystal tuffs. What seemed a fresher sample of a light-gray tuff from a 2 meter thick bed was obtained on road 128 in the southwest corner of Barrio Rubias. It has been nearly completely zeolitized; some authigenic calcite and epidote are also present. The original texture of the tuff bed has been completely destroyed.

Stratigraphic and structural relationships

The Yauco Mudstone seems to be lying unconformably on the Maricao Basalt. In the fault block east of the Monte Membrillo fault different attitudes occur on both sides of the contact; this is further evidence for an unconformable relationship between these two units. Slodowski (1956) and McIntyre (1973) reported that the Yauco Mudstone rests concordantly on the Rio Loco Formation in areas to the west of the Monte Guilarte quadrangle.

In the southwest corner in Barrio Rubias, the Yauco Mudstone concordantly lies below and above the Sabana Grande Formation; the upper contact of the Yauco Mudstone is not exposed in the mapped area. Slodowski (1956) reported that the Yauco Mudstone overlies the Sabana Grande Formation about 6 kilometers northeast of the town of Yauco, although he never observed the contact. In the Maricao quadrangle, immediately to the west, the upper contact of the Yauco Mudstone is faulted (McIntyre, 1973). In the Ponce quadrangle, 30 kilometers to the southeast, the Yauco Mudstone is separated from the overlying rocks by an unconformity (Krushensky and Monroe, 1975). To the west, in the Central La Plata quadrangle, the unit is overlain concordantly by the Maricao Basalt (McIntyre, Aaron, and Tobisch, 1970).

Apparently, the Yauco Mudstone is a lithofacies which does not occupy a single stratigraphic horizon. Complex interfingering of various units occur at several localities (Mattson, 1960; Krushensky and Monroe, 1975) and the sequences found at a given locality cannot be carried elsewhere in the region. The apparent discrepancy in the stratigraphic relationships indicates that the formation does not behave as a simple time-stratigraphic unit. This complex relationship is, as Mattson (1960) pointed out, "a stratigraphical concept of great importance in regions where thick volcanics are deposited with shallow-water sediments".

Minor folds are present in the Yauco Mudstone but none of them seem to be related to major structures since the general attitudes of the beds do not appear to be drastically changed.

One major fold, a syncline, appears to be present in the Indiera Alta fault block. The rocks seem to flatten in attitudes and in some cases near the bottom of the valley of the Rio Prieto the dips are reversed. The north limb of the fold seems to have been faulted, dividing it into two parts. This synclinal structure appears to be a major one involving the entire fault block. The relationships within this syncline indicate that the Yauco Mudstone overlies the Maricao Basalt in this fault block (Plate 1).

Igneous bodies intrude the unit in several places but no metamorphic effects, not even recrystallization of the calcite, were noticed. The only visible effect is the development of a crude cleave, only noticed in thin section, minor faulting and shearing, and some tilting of the beds adjacent to the intrusive bodies. This is very well exposed on a stream 600 meters southeast of Hacienda Fortuna in Barrio Indiera Alta. Here the stream runs along the contact between the Yauco Mudstone and the hornblende porphyry.

The contact between the Yauco Mudstone and the Rio Loco Formation in the fault block east of the Monte Membrillo fault is the Anjilones fault. Attitudes of the Yauco Mudstone become progressively steeper nearer the fault. Right next to the fault the Yauco Mudstone beds become vertical indicating a downward movement of the southern side.

Source and environment of deposition

The abundance of volcanic of volcanic and hypabyssal rock and crystal fragments in the sandstone beds indicate a volcanic, epiclastic source for the clastic material. The subangular to rounded character of the fragments indicates that they have been reworked prior to deposition.

Slodowski (1956) suggested a deep water environment for the deposition of the Yauco Mudstone. He indicated that the material had been transported by turbidity currents to abyssal depths. In the southwest quarter of the Monte Guilarte quadrangle the absence of turbidite characteristics, such as the Bouma internal units (Bouma, 1964), even in the graded beds, suggests that the main mode of transportation was not by turbidity currents, but by normal shallow marine currents. Turbidity currents could have played a major role locally. The massive, non-pillowed lavas of the Sabana Grande Formation, which are concordant and possibly conformable within the Yauco Mudstone, indicate that they were extruded subaerially or in an extremely shallow Yauco sea. Rudist banks have been found in the Yauco Mudstone with the rudist in an upright position; these rudists apparently need shallow waters (R.D.Krushensky, personal communication, 1975). Mattson (1960a, p. 92) described the depositional environment of the Mayaguez group, which includes the Yauco Mudstone as:

> " a tropical to subtropical shallow water area with abundant nearby volcanic activity and with small regions of older rocks above sea level".

All evidence tends to indicate that the Yauco Mudstone was deposited in a shallow marine environment with some volcanic activity occurring in the adjacent areas and some islands shedding the epiclastic detritus. The abundance of the dark brown calcareous clayey matrix and the micritic mud suggest that the environment was predominantly one of low energy. Some surges of high energy, probably due to storms, occurred every now and then producing the calcareous breccias and reworking previously deposited coarse detritus giving rise to the calcareous conglomerates. The relatively great thickness of the unit in southwestern Puerto Rico indicates a tectonically unstable depocenter during Yauco time, with slow subsidence continuing throughout this time interval.

UNNAMED HORNBLENDE BRECCIA UNIT

The unnamed hornblende breccia unit covers about 10 percent of the mapped area and occurs as a northwest southeast trending belt in the east-central part, north and east of Monte Membrillo. The unit has not been named or described anywhere else in southwestern Puerto Rico, and it will not be given a formal name in this report. Good exposures occur on dirt roads which run south and southeast of Hacienda Arbela in Barrio Rio Prieto, in the east-central part of the mapped area. These exposures are herein designated as the type area of the unnamed hornblende breccia unit in the southwest quarter of the Monte Guilarte quadrangle.

No fossils were obtained from this unit. The basis for an age determination is its relationship with the Yauco Mudstone. Since the unit is concordant and probably conformable within the Yauco Mudstone, its age must be that of the Yauco Mudstone. Therefore, the age of the unnamed hornblende breccia unit is Campanian, probably Turonian to Maestrichtian (Upper Cretaceous).

The unit thins to the west, from about 850 meters thick near the east border of the area to about 120 meters in the westernmost outcrop of the unit at the intersection of the Monte Membrillo and Anjilones faults.

Rock descriptions

The unnamed hornblende breccia unit consists mainly of massive, light greenish-gray to light brown (when fresh) volcaniclastic breccias and conglomerates (Fisher, 1961) with minor interbeds of calcareous volcaniclastic sandstones, siltstones and minor claystones. A very striking characteristic is the abundance of hornblende crystals both in the clasts and in the matrix of the coarser rock types. The unit is massive and the bedding is present only in the thin- to medium-bedded calcareous sedimentary rocks which appear to occur as lenses within the unit. The lateral extent of these calcareous beds could not be mapped due to their small size and the degree of weathering in the area. These beds of calcareous sedimentary rocks are well exposed om a small road which runs south from road 374 to the east side of Monte Membrillo. Locally, where the massive breccias and conglomerates are slightly weathered, bedding planes can be noticed (Figure 23). This was observed in the type exposures near the upper contact with the Yauco Mudstone.

The rocks weather to a light yellowish-brown saprolitic soil which contains spheroidal boulders of fresh rocks. This saprolitic soil in some places retains the original textures of the rock, but elsewhere the textures have been completely destroyed.

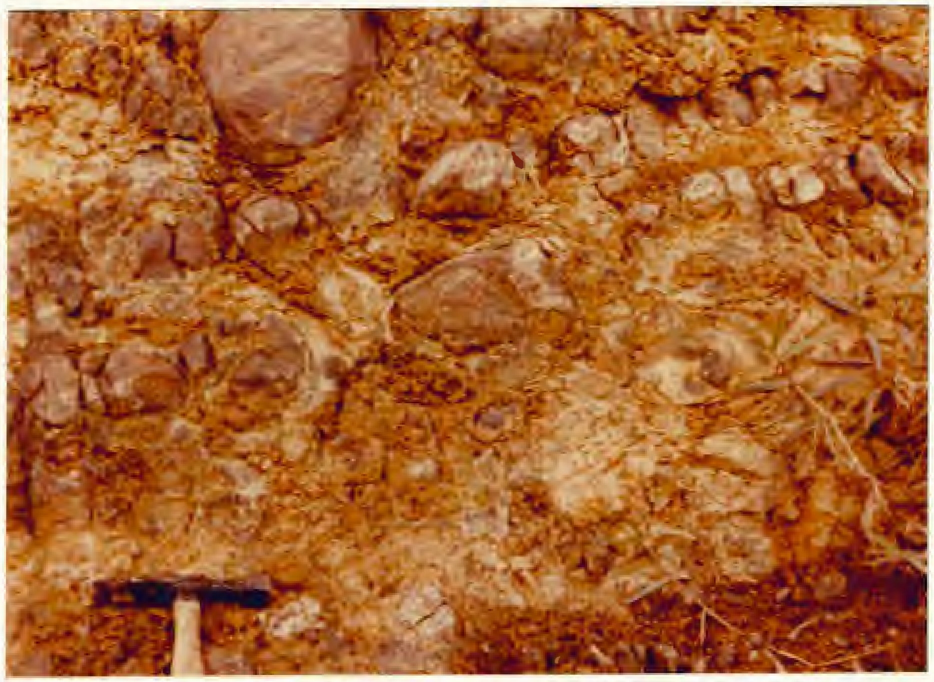

Figure 23. Bedding in the weathered unnamed hornblende breccia unit on a small trail south of Hacienda Arbela in Barrio Rio Prieto.

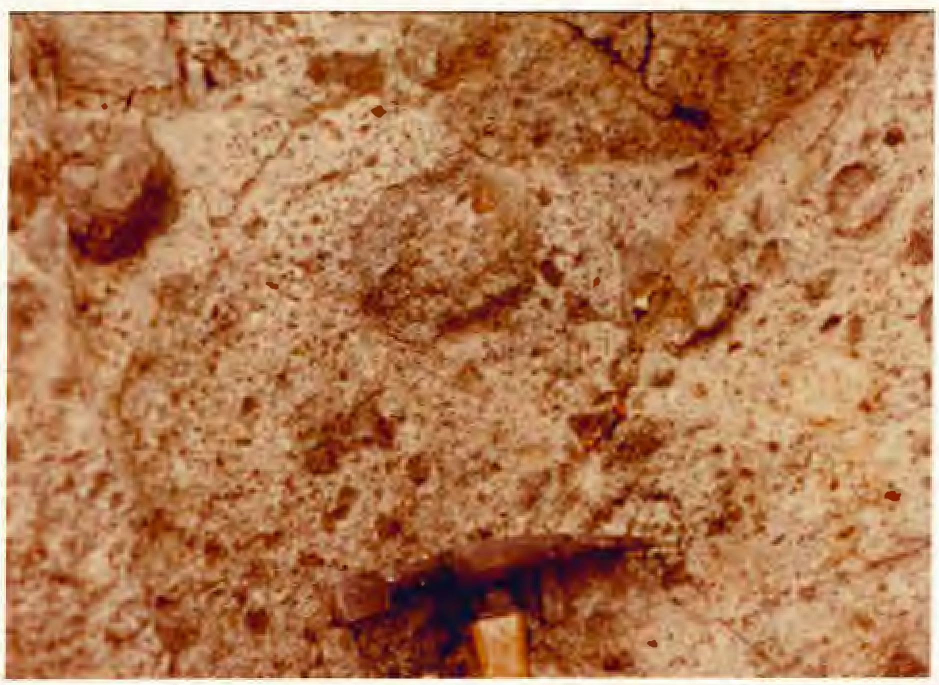

Figure 24. Close up of a volcaniclastic conglomerate of the unnamed hornblende breccia unit on a small road east of Monte Membrillo in Barrio Rio Prieto.

<u>Volcaniclastic breccias and conglomerates</u> make up about 95 percent of the unit. They are unsorted, with polymictic angular to subrounded clasts. The clasts make up to 80 percent of the outcrops and are hornblende and augite porphyry and trachytic volcanic rock fragments, and in most cases are parabreccias and paraconglomerates as the larger clasts do not touch each other (Figure 24).

The matrix is sand to mud-sized and is made mainly of volcanic rock and crystal fragments ranging from silt to 2.0 millimeters with an average between 0.5 and 1 millimeter. The rock fragments locally comprise 70 percent of the matrix and are hornblende porphyry, plagioclase porphyry, augite porphyry, and quartz-plagioclase porphyry with minor chert, glass, and limestone fragments. Some of the rock fragments are dacitic-rhyolitic in composition. This was determined by staining for potassium feldspars, which could not be distinguished optically. Some of the rock fragments have been altered to chlorite or epidote or a combination of these. Some of the hornblende-bearing rock fragments are similar in texture to the hornblende porphyry intrusion; other fragments are finer-grained. The angular to subangular crystal fragments, which locally constitute up to about 35 percent of the matrix, are mainly hornblende, augite, and plagioclase with minor quartz, opaques and fossils (Figures 25 and 26; Table 5).

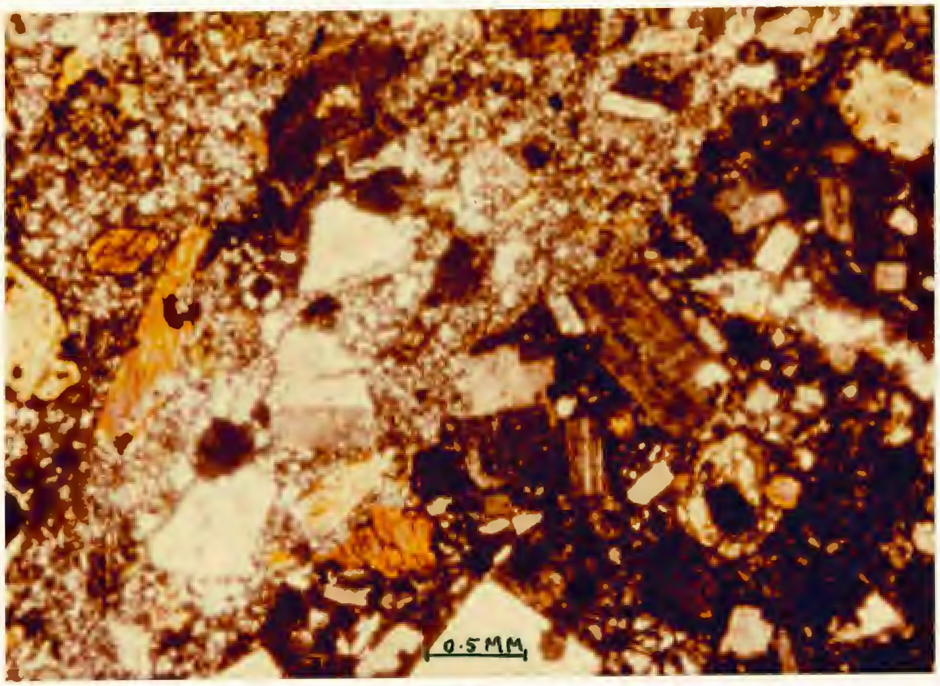

Figure 25. Sample 7/30/75-3 Matrix of a breccia of the unnamed hornblende breccia unit. Fragment to the right is a mafic volcanic rock fragment. To the left is a hornblende porphyry rock fragment. Crossed nicols.

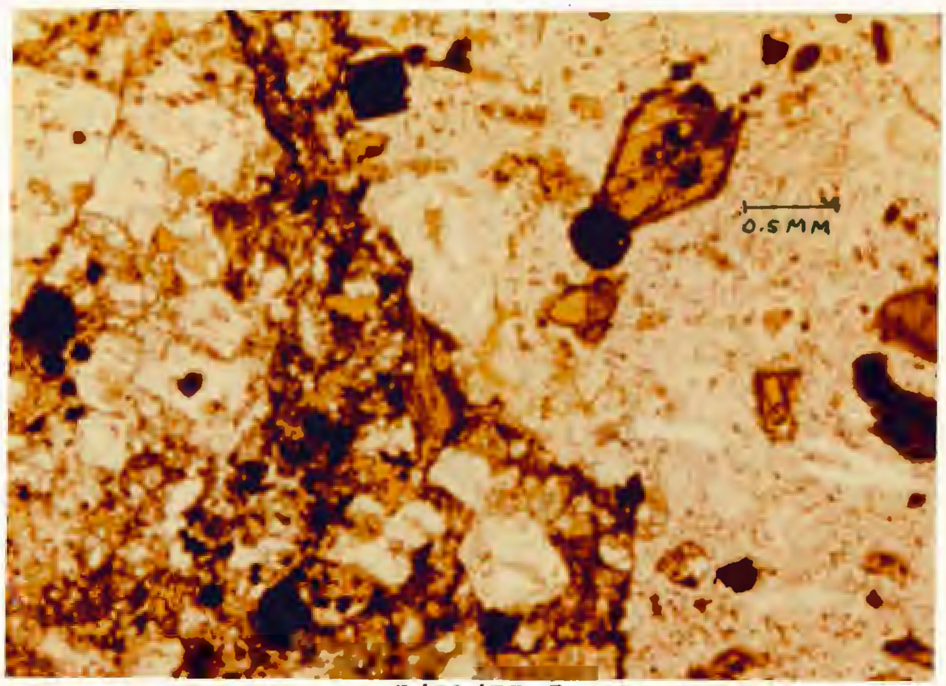

Figure 26. Sample 7/29/75-5 Matrix of a breccia of the unnamed hornblende brecia unit. A hornblende porphyry rock fragment to the right. Matrix consist of hornblende and augute rock fragments and crystals of hornblende and plagioclase. Some epidote is also present. Plain light.

Table 5.
MODAL ANALYSES OF THE VOLCANICLASTIC ROCKS OF THE UNNAMED HORNBLENDE BRECCIA UNIT

CLASTIC GRAINS	7/31/75-3	8/4/75-3	8/24/75-4
Minerals			
Plagioclase	10.5	0.9	0.6
Augite	1.5	1.8	-
Hornblende	1.5	0.9	0.9
Quartz	2.4	tr	-
Opaques	tr	0.9	-
TOTAL	15.9	4.5	1.5
Rock fragments			
Volc.-hypabyssal			
Augite porph.	0.5	1.1	-
Augite-plag.poph.		0.9	-
Augite-plag.quartz porph.	-	-	-
Hornbl. poprh.	0.3	45.6	57.2
Hornbl.-aigite porph.	-	18.1	-
Plag.porph.	10.5	4.4	13.1
Plag.-quartz,volc. frag.	2.9	1.1	-
Plag.-rich frag.	-	5.5	5.6
Other			
Altered frag.	12.8	2.9	1.1
Chert frag.	4.7	-	0.4
TOTAL	31.7	79.6	77.4
Matrix-cement			
Epidote		12.4	16.0
Chlorite	-	2.9	4.7
Calcite	51.7		
	99.3	99.4	99.6

7/31/75-3 Calcareous sandstone interbedded with the unnamed hornblende breccia unit from an outcrop on a small road 0.4 kilometer east of Hacienda Asuncion in Barrio Rio Prieto.

8/4/75-3 Breccia of the unnamed hornblende breccia unit from an outcrop on a small road about 1.1 kilometer east of Hacienda Maria Antonia in Barrio Indiera Alta.

8/24/75-4 Breccia of the unnamed hornblende breccia unit from an outcrop on a small road 0.4 kilometer southeast of Hacienda Asuncion in Barrio Rio Prieto.

The euhedral to subhedral hornblende crystals are in most cases totally altered to chlorite and magnetite. The plagioclase crystals are euhedral to subhedral and generally turbid and sericitized, and twinned following albite and pericline laws. The augites, which are subhedral to anhedral, are mainly unaltered but some show alteration to chlorite and calcite. The quartz is generally subrounded.

The matrix between the sand grains is a very fine-grained chloritic material, which constitutes up to 15 percent of the total matrix. It shows alteration to epidote.

<u>The calcareous volcaniclastic sandstones</u> (Fisher, 1961), are made up mainly of rock and crystal fragments ranging in size from 0.25 to 2.0 millimeters with an average between 0.5 and 1 millimeter. The rounded to subrounded rock fragments make up to 60 percent of the rock; they are composed mainly of trachytic to pilotaxitic volcanic and limestone fragments. Some of the volcanic fragments show alteration to chlorite. The angular to subangular crystal fragments, which comprise up to 35 percent of the rock, are mainly quartz, plagioclase hornblende and augite. Minor fossils and opaques are also present (Table 5).

The clastic plagioclase grains are euhedral to subhedral and are generally turbid and sericitized; most are twinned following albite and pericline laws and some are zoned. Some of the augite grains, which are subhedral to anhedral, are twinned and zoned, and some show alteration to chlorite. The quartz is typically anhedral but some euhedral grains were noticed.

A dark brown calcareous clayey matrix constitutes up to 20 percent of the rock; in some cases it has been recrystallized to a fine-grained calcite cement.

The calcareous siltstones are light to dark gray to light brown and are made up of silt-sized angular fragments of quartz, plagioclase, and augite with minor opaques and fossils in a dark brown calcareous clayey matrix.

Claystones, light brown in color, are present in minor amounts and are made up mainly of a dark brown calcareous clay.

Structural and stratigraphic relationships

The unnamed hornblende breccia unit seems to be lying concordantly and probably conformably within the Yauco Mudstone. The unit is faulted in the west by the Membrillo and Anjilones faults. It is intruded near its northeast margin by an augite porphyry intrusive body but no significant metamorphic effects were noticed.

Source and environment of deposition

The abundance of volcanic and hypabyssal rock and crystal fragments strongly indicates an igneous source for most of the material. The presence of acidic rock fragments indicates that for the firs time acidic hornblende-rich rocks were exposed and were being eroded. The lack of lava flows and the absence of pyroclastic material suggests that no major volcanic activity was taking place in the adjacent areas during the deposition of this unit, and therefore the bulk of the material was probably derived from pre-existing rocks.

The angularity of the clasts and the abundance of unstable rock and crystal fragments probably indicate a low energy environment of deposition with little or no reworking of the material. The mode of transportation of the material to the basin of deposition must not have had much effect on the sorting and rounding of the fragments. Perhaps massive "mudflows" could have been triggered by tropical rains in a tectonically unstable environment. This process would give rise massive erosion and transportation with little reworking of the material. Deposition of the parabreccias and paraconglomerates ceased from time to time and calcareous sediments were deposited in a shallow sea. Since this unit is interbedded within the Yauco Mudstone, the overall environment was probably very similar. This environment, as explained in the Yauco Mudstone section, was probably a shallow marine environment with some surrounding areas above sea level. Apparently, the unnamed hornblende-breccia unit was derived from one of these positive areas which was predominantly made up of volcanic and hypabyssal hornblende-rich rocks.

SABANA GRANDE FORMATION

The Sabana Grande Formation was named by Slodowski (1956) for rocks cropping out near the town of Sabana Grande on road #2, about 10 kilometers southwest of the Monte Guilarte quadrangle. The rocks, which are exposed north and northwest of the town, consist of an assemblage of andesitic lava flows with some dark, calcareous mudstones (Slodowski, 1956). The flows in the type area are pyroxene or hornblende-rich, porphyritic, and commonly amygdular. Plagioclase commonly makes up more than 50 percent of the rock, ferromagnesian minerals less than 30 percent, and groundmass about 20 percent. Mattson (1960) included in the formation breccias, tuffs and lava flows of basaltic and andesitic composition.

The Sabana Grande Formation in the southwest quarter of the Monte Guilarte quadrangle covers about 1 percent of the area and occurs at only two localities, in the fault block on the western part of Barrio Rubias.

No fossils were obtained from this unit, but a sample of the Yauco Mudstone, which was collected from a horizon stratigraphically lower, yielded a Maestrichtian age. Slodowski (1956) assigned a Turonian to Santonian age (Upper Cretaceous) on the basis of Foraminifera. Mattson (1960), based on stratigraphic position, assigned a Turonian to Campanian age.

The age of the Sabana Grande Formation is considered to be Turonian to Campanian, but could be as young as Maestrichtian.

The thickness of the unit in the mapped area is 70 meters. The unit is faulted to the east. Slodowski (1956) estimated 5,000 meters as the thickness in the type area.

Rock descriptions

The Sabana Grande Formation in the Monte Guilarte quadrangle consists mainly of light greenish-gray, porphyritic to phaneritic, fine- to medium-grained, amygdaloidal, massive, probably basaltic lava flows with minor flow breccias and pyroxene-rich sandstones. The unit weathers to a light orange saprolitic soil.

The lava flows are holocrystalline in texture and are made up of about 5 to 8 percent augite and plagioclase phenocrysts in a fine-grained groundmass. The euhedral to subhedral plagioclase crystals are as much as 3 millimeters in length and make up from 40 to 45 percent of the rock. They are usually twinned and show alteration to chlorite, calcite, and sericite. Plagioclase composition could not be determined optically due to the high degree of alteration. Anhedral to subhedral augite crystals, which are biaxial (+) with a 2V of about 45°, are as much as 2 millimeters in length and constitute from 20 to 30 percent of the rock. They show alteration to chlorite, calcite, and epidote. The opaque minerals, which make up to 5 percent of the rock, are mainly magnetite but include minor amounts of hematite. The felty to pilotaxitic groundmass consists of plagioclase, augite, opaques, and alteration products such as chlorite, calcite, and epidote. The lavas are commonly amygdular with amygdules making up to 30 percent of the rock; calcite, chlorite, quartz, and zeolites are the minerals in the amygdules. Individual flows are estimated to be from 5 to 10 meters thick; lack of good outcrops and the degree of weathering does not permit a more accurate measurement. Unlike the flows described by Slodowski (1956), the flows mapped in the southwest corner of the Monte Guilarte quadrangle do not contain hornblende (Table 6).

The pyroxene-rich volcaniclastic sandstones occur as thin interbeds and are up to 2 meters thick. They are light brown, coarse-grained, and highly weathered so no sample was collected. The base of the formation, exposed on road 128, consists of about 0.75 meter of this coarse-grained sandstone. The same lithology is also present between the flows; at least four beds are exposed along the road.

Stratigraphic structural relationships

The Sabana Grande Formation is concordant within,

Table 6.

MODAL ANALYSES OF THE SABANA GRANDE FORMATION LAVAS

	7/7/75-6	7/8/75-7
Groundmass		
Augite	41.2	38.2
Plagioclase	54.0	61.1
Opaques	4.8	0.6
	99.9	99.9
Percent of amygdules in the rock.	26	30

7/7/75-6 Lava of the Sabana Grande Formation from outcrops on road 128 in the southwest corner of the area in Barrio Rubias.

7/8/75-7 same locality as sample 7/7/75-6 and probably conformable, in the Yauco Mudstone. The unit seems to be a tongue of lava flows and sediments within the Yauco Mudstone. In the type area, Slodowski (1956) reported the unit in depositional contact over serpentinites and beneath the Yauco Mudstone, although he never observed the contacts as they are not exposed in his area. In the Mayaguez area, Mattson (1960) reported that the unit lies between the Yauco Mudstone and the Parguera Limestone. Apparently the Sabana Grande Formation does not occupy a single stratigraphic horizon and it seems to intertongue with the Yauco Mudstone giving rise to the apparent discrepancy in stratigraphic relationship.

Environment of deposition

The massive, unpillowed lava flows strongly suggest subaerial deposition. Since the unit is concordant within the Yauco Mudstone there probably was no major break in sedimentation and the contact simply represents a sudden influx of lava flows into the basin. These lavas were probably extruded into a very shallow Yauco sea or in a tidal environment producing no pillows; subsequently, the interflow sandstones were formed by reworking.

HORNBLENDE PORPHYRY INTRUSIONS

The hornblende porphyry intrusions cover approximately 15 percent of the area of the southwest quarter of the Monte Guilarte quadrangle. The main intrusive bodies are located in Barrios Naranjo, and Aguas Blancas; in Barrio Indiera Alta, and a small body occurs in Barrio Rio Prieto north of Hacienda Santa Clara. Minor dikes occur elsewhere but could not be mapped due to their small size. The contacts between the hornblende porphyry and the adjacent rocks are very sharp.

The intrusions consist mainly of a dark to light greenish-gray(when fresh), porphyrytic, massive, andesitic, intrusive rock. The characteristic phenocryst is hornblende. The unit makes massive outcrops and weathers to a light puplish-white saprolitic soil which may contain spheroidal boulders of fresh rock. The ferromagnesian minerals are readily weathered and no original textures are preserved.

A typical hornblende porphyry cosist of 5 to 15 percent hornblende phenocrysts ranging in size from less than 1 millimeter to as large as 6 millimeters long and from 1 to 2 millimeters thick, and 20 to 50 percent plagioclase with an average of 30 percent. The plagioclase phenocrysts range in size from 1 to 5 millimeters. All of the phenocrysts are in a fine-grained aphanitic matrix. See Table 7 for modal analy-

Table 7.

MODAL ANALYSES OF THE ROCKS OF THE HORNBLENDE PORPHYRY INTRUSIONS

	7/2/75-2	7/8/75-4	7/3/75-1	7/18/75-2
Phenocrysts				
Hornblende	2.8	4.7	1.2	4.1
Magnetite	2.3	5.2	1.0	3.2
Pyroxene	2.3	7.1	11.7	7.6
Plagioclase	19.7	27.3	53.7	32.2
Quartz	3.6	-	-	-
Opaques	3.1	5.3	8.1	5.0
Groundmass	66.0	50.1	24.0	47.4
	99.8	99.7	99.7	99.5

7/2/75-2 Hornblende porphyry from an outcrop on a small trail 1 kilometer south of Hacienda Resurreccion in Barrio Naranjo.

7/8/75-4 Hornblende porphyry from an outcrop on a small trail 0.4 kilometer north of Hacienda Leonor in Barrio Aguas Blancas.

7/3/75-1 Hornblende porphyry from an outcrop on a small trail 1.1 kilometer south of Hacienda Resurreccion in Barrio Naranjo.

7/18/75-6 Hornblende porphyry from an outcrop on road 128, kilometer 29.8 in Barrio Indiera Alta.

ses. Augite is present as phenocrysts in some of the intrusive bodies and locally constitutes 10 to 20 percent of the rock. The phenocrysts range in size from 1 to 5 millimeters.

The hornblende phenocrysts are euhedral to subhedral and contain magnetite inclusions, and are usually rimmed by fine-grained magnetite (Figure 27). Hornblende commonly shows alteration to chlorite and in a few cases it has been completely replaced by calcite. This replacement of calcite generally occurs in rocks with high quartz content.

The plagioclases are euhedral to subhedral and usually twinned, following albite and pericline laws, and are sometimes zoned. The plagioclase compositions range from An_{40} to An_{60}.

The augite crystals are euhedral to subhedral and sometimes zoned, and are in some cases twinned; they are biaxial (+) with a 2V of about 45^{o} (Figure 28). They are usually poikilitic enclosing grains of magnetite but also can enclose minor apatite and plagioclase crystals. Some augite crystals show replacement by hornblende along cracks.

Quartz is generally absent but locally is found as phenocrysts in amounts up to 15 percent of the rock. They are typically dusty, show embayments, are undulose, and are rounded to subrounded due to magmatic resorption (Figure 29). Some quartz appears to

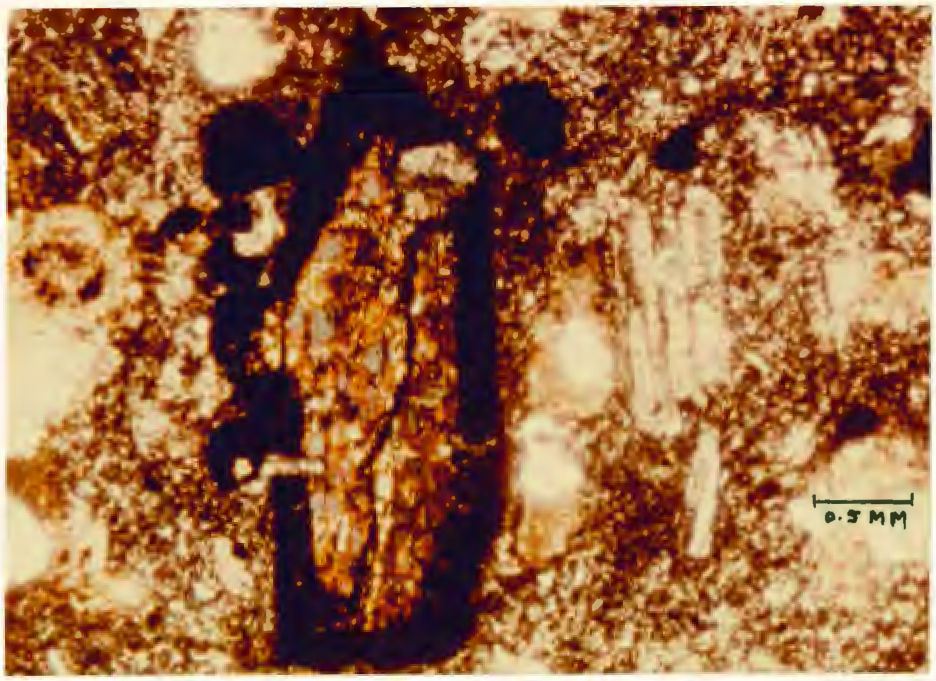

Figure 27. Sample 7/2/75-2 Hornblende phenocryst rimmed by magnetite. White clear patches are quartz probably filling minor amygdules. Crossed nicols.

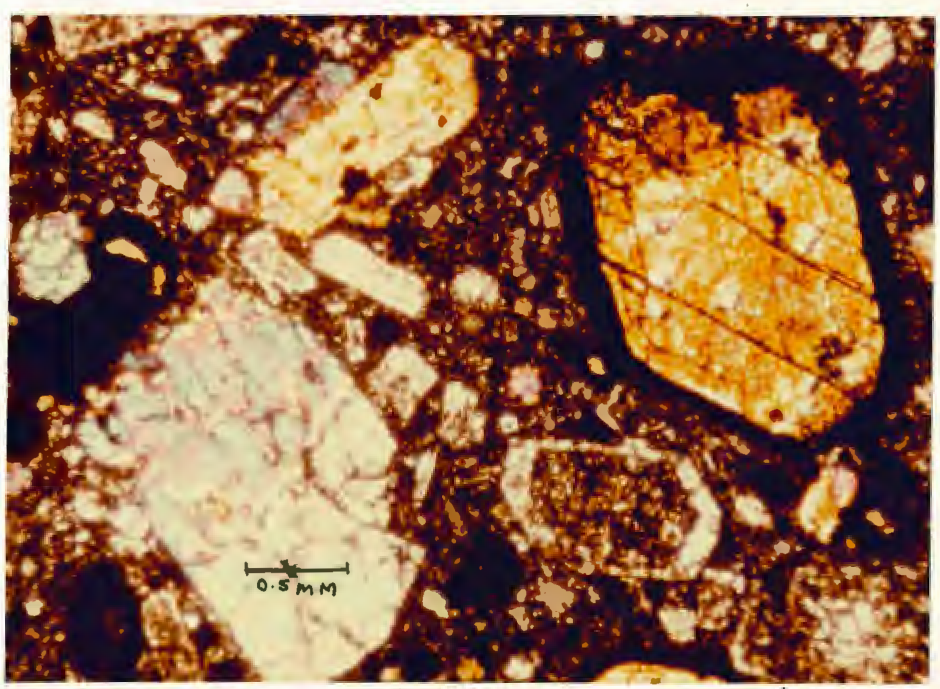

Figure 28. Sample 7/8/75-4 Hornblende (upper right) and augite (lower left) phenocrysts in a fine-grained matrix. Crossed nicols.

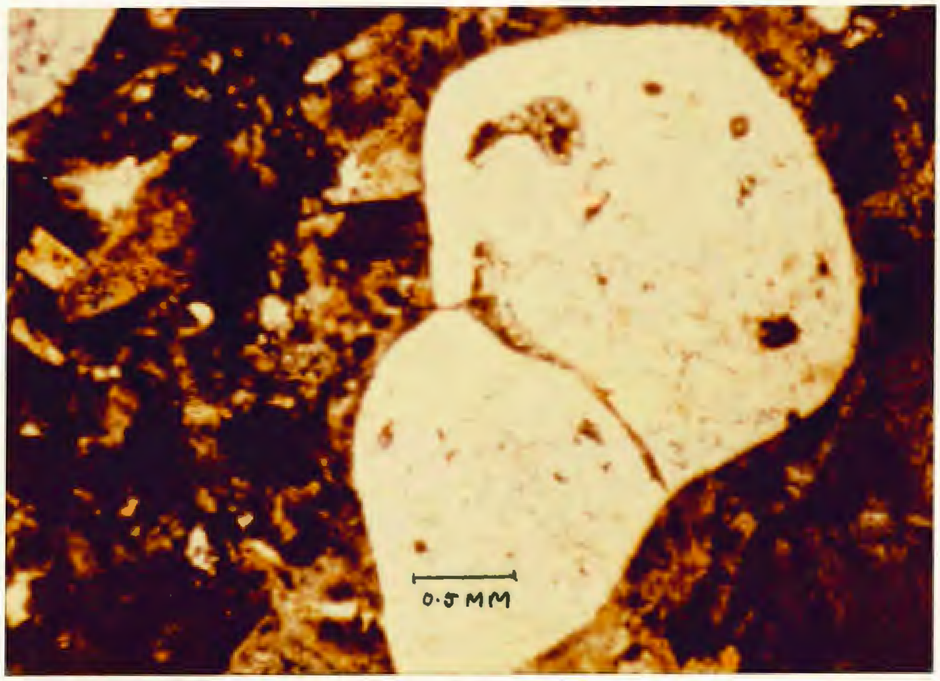

Figure 29. Sample 7/18/75-2 Resorbed quartz phenocryst in the hornblende porphyry. Crossed nicols.

be filling minor vesicles. Opaque minerals, mostly magnetite, constitute up to 10 percent of the rock.

The aphanitic groundmass is felty to pilotaxitic consists mainly of fine-grained hornblende plagioclase, magnetite, augite, and quartz. It also contains alteration products such as chlorite, calcite, and epidote.

The fine-grained size of the matrix and the possible presence of vesicles indicate that the intrusions were emplaced at a very shallow depth. There are no visible contact-metamorphic effect on the adjacent country rock. A good example of this is on a stream about 600 meters southeast of Hacienda Fortuna in Barrio Indiera Alta where the contact between the Yauco Mudstone and the hornblende porphyry intrusion is found in the stream. Examination of a sample of the Yauco Mudstone from less than one meter from the contact shows no evidence of contact-metamorphic effects, not even recrystallization of the calcite. The only effect is a tilting of the beds adjacent to the contact and the development of a crude cleavage only noticed in thin sections. This supports the idea of a shallow emplacement depth.

In some cases xenoliths of country rocks are found in the intrusion. A good example is on road 128 at kilometer 29.9 in Barrio Indiera Alta. In this roadcut unaltered xenoliths of calcareous mudstone, similar to the rocks of the Yauco Mudstone, occur in a chaotic arrangement within the intrusion.

The presence of vesicles and the abundance of magnetite rims around most hornblende phenocrysts suggest that the intrusion was accompanied by a sudden release in volatile pressure.

Between Hacienda Vicario and Quebrada Grande in Barrio Aguas Blancas, the hornblende porphyry and the augite porphyry (described below) are in contact with each other but their age relationship is not clear. The exact age of the hornblende porphyry is not known but based on cross-cutting relationship a relative age can be established. It intrudes the Yauco Mudstone and the Maricao Basalt; both range in age from Turonian to Maestrichtian (Upper Cretaceous). Therefore a Late Cretaceous to Tertiary age is assigned to the hornblende porphyry intrusions in this area. Similar hornblende-bearing intrusions in the Ponce quadrangle, about 30 kilometers to the southeast, have been assigned an Eocene age on the basis of stratigraphic relationships (Krushensky and Monroe, 1975).

AUGITE PORPHYRY INTRUSIONS

The augite porphyry intrusions cover approximately 10 percent of the area of the southwest quarter of the Monte Guilarte quadrangle. The main intrusive bodies are located in the southern part of the mapped area in Barrios Rubias, Naranjo, Aguas Blancas; and in the eastern border of the area, about 500 meters northeast of Hacienda Arbela in Barrio Rio Prieto. Minor dikes occur elsewhere but could not be mapped because of their small size. Contacts between the augite porphyry and the adjacent country rocks are very sharp and intrusion breccias are developed locally along the margins of some of the igneous bodies.

The intrusions consist mainly of greenish-gray to dark gray (when fresh), porphyritic, massive, basaltic intrusive rock. The characteristic phenocryst is augite. The unit makes up massive outcrops and steep slopes and weathers to a dark orange-brown saprolitic soil which may contain spheroidal boulders of fresh rock. This saprolitic soil retains all of the original textures of the rock. This characteristic is very helpful in mapping deeply weathered areas.

A typical augite porphyry consists of 10 to 40 percent augite phenocrysts ranging in size from 2 to 6 millimeters, and 20 to 40 percent plagioclase phenocrysts ranging in size from 1 to 4 millimeters, all in a fine-grained aphanitic groundmass.

The augite phenocrysts are euhedral to anhedral and some are twinned and zoned. They are typically poikilitic, enclosing magnetite crystals, and are biaxial (+) with a 2V of about 45^{o}. They show alteration to chlorite, calcite, fine-grained uralite?, and hematite. In the saprolitic soil the augite crystals have been completely replaced by limonite (Figures 30 and 31). The plagioclase phenocrysts are euhedral to subhedral, generally twinned following albite and pericline laws, and zoned. They commonly show alteration to calcite, chlorite, sericite, and kaolinite . In the zoned crystals the alteration occurs in distinct zones, with the core most altered. The plagioclases range in composition from An_{50} to An_{70}. Opaque minerals, generally magnetite, make up to 10 percent of the rock and are typically concentrated within the augite crystals. Quartz is present in only certain localities and does not exceed more than 5 percent of any sample studied. The aphanitic groundmass is felty to pilotaxitic in texture, makes from 15 to 60 percent of the rock and consists mainly of fine-grained augite, plagioclase, opaques, and minor alteration products such as calcite, chlorite, epidote, and hematite.(Table 8.)

The fine-grained matrix and the lack of contact-metamorphic effects on the adjacent country rock indicate a shallow depth of emplacement. The only

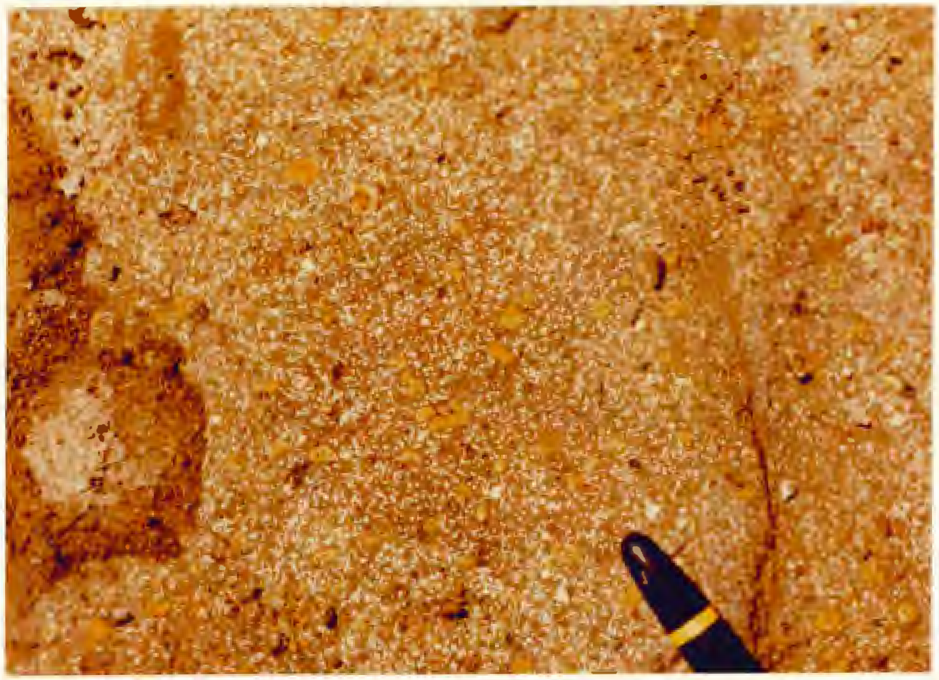

Figure 30. Saprolite of the augite porphyry intrusion in a ditch on a small road about 600 meters northwest of Hacienda Vicario in Aguas Blancas.

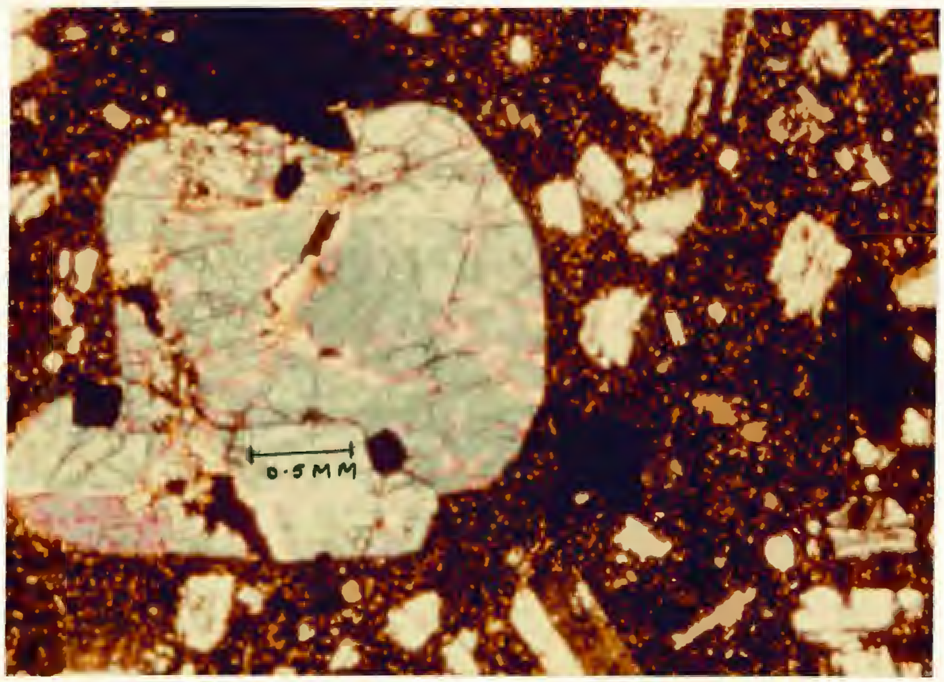

Figure 31. Sample 8/12/75-1 Augite porphyry intrusion. Augite phenocrysts in a fine-grained matrix.

Table 8.

MODAL ANALYSES OF THE ROCKS OF THE AUGITE PORPHYRY INTRUSIONS

	7/8/75-1	7/10/75-3	8/12/75-1	7/25/75-2
Phenocrysts				
Augite	12.8	14.4	15.8	35.3
Plagioclase	33.0	21.1	25.0	39.7
Quartz	-	5.2	tr	-
Opaques	2.6	6.1	2.5	6.1
Groundmass	51.3	53.2	56.1	18.7
Apatite	-	-	-	tr

7/8/75-1 Augite porphyry from an outcrop on a small road about 100 meters south of Hacienda Vicario in Barrio Aguas Blancas.

7/10/75-3 Augite porphyry from an outcrop on a small trail 0.4 kilometer northwest of Hacienda Vicario in Barrio Aguas Blancas.

8/12/75-1 Augite porphyry from an igneous body 3.0 kilometers southeast of the town of Castaner in Barrio Guayo.

7/25/75-2 Gabbroic rock from a small stock on road 128 at kilometer 41.6 in Barrio Bartolo.

visible effect in the country rock is the tilting of beds next to the contacts, as in the case of the hornblende porphyry intrusions.

The intrusion breccia blocks along the margins of some of the bodies are mineralogically similar to the bulk of the intrusions but differ greatly in grain size. These blocks are generally finer-grained and contain some vesicles and glass.

The intrusive bodies of the southern part of the area have intruded the Maricao Basalt, which is composed mainly of augite-bearing volcaniclastic breccias. Where the saprolitic cover is deep or where the border zones of the intrusions are brecciated the contact between these two units is difficult to define.

A small intrusive body at kilometer 41.6 on road 128 near the border of Barrio Indiera Alta and Bartolo differs greatly from the rest of the augite porphyry intrusions. This body is gabbroic in texture and is made up mainly of poikilitic augites and euhedral plagioclases both ranging from 1 to 4 millimeters in length. This rock has a different magmatic history but since its areal extent is so small it has been included with the augite porphyries.

The augite-bearing intrusions have not been dated and their relationship with the hornblende porphyry is not clear. Based on cross-cutting relationships a relative age can be established. The augite porphyry bodies intrude the Yauco Mudstone and the Maricao Basalt; both range in age from Turonian to Maestrichtian (Upper Cretaceous). Therefore, a Late Cretaceous to Tertiary age is assigned to the augite porphyry intrusions in this area.

SUMMARY OF THE ENVIRONMENT OF DEPOSITION

The bulk of the Upper Cretaceous rocks of the southwest quarter of the Monte Guilarte quadrangle consist of a volcanic-sedimentary sequence more than 2,580 meters thick. All of the evidence seems to suggest that most of the rocks were deposited in a tropical shallow-marine environment. During Rio Loco time there was abundant volcanic activity, but during the deposition of the rest of the units, with the exception of the Sabana Grande Formation, little volcanic activity was going on. The general absence of pyroclastic material and lava flows tend to support this.

The lack of sorting and rounding of the sediments indicates that the material suffered little reworking. A tectonically unstable basin would be necessary for a rapid burial of the material. Most of the units contain calcareous sedimentary beds or lenses, which apparently were deposited during periods of slow terrestial sedimentation. In some cases the calcareous material was reworked; this probably is indicative of minor storms in the basin rather than to uplift and erosion.

The abundance of volcanic, hypabyssal, and intrusive rock fragments of various types tends to suggest that the volcaniclastic sediments are probably largely epiclastic in origin, derived from pre-existing rocks.

The Bermeja Complex, probably the basal unit of the volcanic accumulation, is made up mainly of serpentinite, amphibolite, and silicified volcanics and/or chert (Mattson, 1960). It is exposed to the west of the Monte Guilarte quadrangle (Figure 2). Slodowski (1956) and Mattson (1960) indicated that the basal Bermeja Complex was exposed and being eroded by Late Cretaceous time. In the sedimentary rocks of the mapped area no major contribution from this source was noticed, and therefore, probably most of the volcaniclastic material of the southwest quarter of the Monte Guilarte quadrangle was derived from the north and the east where older rocks of Early Cretaceous age do occur. These consist of pyroclastic volcanic rocks (Jayuya Tuff) and basaltic and andesitic flows and volcanic sandstones and siltstones, limestones, and tuffs (Robles Formation). Glover (1971) reported a northerly source for the Upper Cretaceous Achiote Conglomerate and Criblanco Formation in the Coamo area, about 40 kilometers southeast of the Monte Guilarte quadrangle. He used as evidence the general strike of the facies changes and the thickness of the units.

The Foraminifera identified from the calcareous rocks of the mapped area apparently lived in a warm shallow-marine environment (Galloway, 1933). Mattson (1960) reported that Late Cretaceous reefs developed in the southwest part of the island (Parguera Limestone and Melones Limestone). The presence of rudist banks in the Yauco Mudstone in the Yauco quadrangle (R.D.Krushensky, 1976, personal communication) supports the concept of a shallow marine environment. All of this is in agreement with paleoclimatic evidence which indicates that the Caribbean area had a subtropical to tropical climate by Late Cretaceous time, with the paleo-equator approaching its present position (Dott and Batten, 1976, p.374).

The presence in some samples of both relatively fresh plagioclase and altered plagioclase of the same approximate composition suggests that some of the alteration observed in the rocks could be due to Cretaceous weathering of source rocks.

STRUCTURAL GEOLOGY

The southwest quarter of the Monte Guilarte quadrangle is located about 8 kilometers south of the southern Puerto Rico fault zone, which divides the central block from the southern block (Figure 2). This zone strikes northwest-southeast and movement along it has been mainly vertical and left-lateral (Glover, 1971). This fault zone has been projected offshore along prominent bathymetric lineaments and along discontinuities shown on the total magnetic intensity map (Glover, 1971), and it is interpeted to be part of the Greater Antilles fracture system.

Structural deformation in the mapped area is predominantly represented by faults. Minor folds occur in the area and they are best noticed in the Yauco Mudstone where the abundance of attitudes permits an excellent control on the structure. Small folds are invariably present in the Yauco Mudstone but as mentioned earlier, they are related to soft sediment deformation. There is a major northwest trending syncline located in the west-central part of the area in Barrio Indiera Alta; minor subsidiary folds occur in the southern limb (Plate 1). The folding is obviously post-Yauco and since the Yauco Mudstone can be as young as Maestrichtian in age, the folding event can be as old as Maestrichtian. If this is true, then it fits the regional pattern of deformation in western Puerto Rico which occurred in four periods: (1) pre-Cenomanian? ; (2) Maestrichtian; (3) late Eocene-early Oligocene; and (4) post-middle Miocene (Mattson, 1960).

Slodowski (1956) reported a syncline in Barrio Rio Prieto. However, no evidence for the syncline indicated by Slodowski was noted during this study; instead the Monte Membrillo fault occupies this position.

Faulting is more common than folding in the rocks of the southwest quarter of the Monte Guilarte quadrangle. Although the actual fault planes are rarely seen, their presence is deduced by such evidence as shear zones, abrupt juxtaposition of lithologies, and by the aberrant attitudes. The two most prominent faults in the area are the northwest-southest trending Monte Membrillo fault and the east-west trending Anjilones fault.

The Anjilones fault was previously recognized by Slodowski (1956) but he failed to map its termination against the Monte Membrillo fault. The Anjilones fault does not show any major fault gouge or shear zone; it separates the Yauco Mudstone in the south and the Rio Loco Formation in the north (Plate 1). Dips within the Yauco Mudstone increase toward the north as the fault is approached (Plate 2). This seems to indicate that the southern side was downthrown relative to the northern side. In the northwestern corner of the area, the Rio Loco Formation is in fault contact with the Maricao Basalt. The contact between these two units is vertical and it is very sharp; a good exposure is along the Rio Prieto dam.

McIntyre (1973) reported a major left-lateral fault in the Maricao quadrangle and its extension into the Monte Guilarte quadrangle lies near the Anjilones fault; he measured a horizontal displacement of 11 kilometers. In the mapping of the southwest quarter of the Monte Guilarte quadrangle no evidence was found for a major left-lateral fault. Although there are minor shears between the Anjilones fault and the western margin of the quadrangle, these can be directly related to other minor faults in the area. Certainly none of the shears noticed was caused by a major left-lateral fault. More detailed mapping in the vicinity of the Anjilones fault and in the northwest margin of the area will be necessary to clarify this discrepancy.

The Monte Membrillo fault is a northwest-southeast trending lineament which cuts accross the southwest quarter of the Monte Guilarte quadrangle. Small shears, abruptly terminated dikes, and abrupt juxtaposition of lithologies are present along this fault. The actual fault plane was never observed due to the thick soil cover. The Monte Membrillo fault apparently postdates the Anjilones fault and other minor faults in the northwest part of the area since it cut across them.

A small fault block containing rocks of the Rio Loco Formation occurs in the northwest corner of the area.

The faults on the north and south side of this block are apparently vertical and are characterized by the juxtaposition of lithologies. All of the other faults are accompanied by shearing and aberrant attitudes in the Yauco Mudstone.

The unnamed fault in the southwest corner of the area in Barrio Rubias separates the Yauco Mudstone in the west from the Maricao Basalt in the east. The fault is concealed under thick saprolitic soil. The evidence for this fault is the abrupt juxtaposition of lithologies, especially that of the Yauco Mudstone against the augite porphyry intrusive. The attitudes of the Yauco Mudstone in this area tend to indicate that the intrusion was not forcibly emplaced into the Yauco Mudstone as is the case in other areas where the Yauco Mudstone has been intruded. This strongly suggests that the juxtaposition is due to faulting and not to intrusion (Figure 5; Plate 1).

Other faults in the map area are characterized by small shears and fault gouges, the widest about 2 meters wide. Minor faults and shears are invariably present in the Yauco Mudstone where it has been intruded by igneous bodies.

Faulting apparently postdates folding and its age is Upper Cretaceous or later since the faults cut all of the units in the area.

GEOLOGIC HISTORY

The earliest volcanic and sedimentary episode in the southwest quarter of the Monte Guilarte qaudrangle is represented by the Rio Loco Formation. Extrusion of subaqueous lava flows and deposition of volcaniclastic breccias and conglomerates and minor calcareous sedimentary rocks characterized Rio Loco time. Little explosive volcanic activity occurred; the sediments probably were deposited during times of no volcanic activity. Islands in nearby adjacent areas probably contributed the volcaniclastic detritus.

The next recorded event is the deposition in a tropical shallow marine environment of the massive Maricao Basalt, with little or no explosive volcanic activity going on. The bulk of the volcaniclastic sediments were derived mainly from older volcanic and hypabyssal rocks which were exposed above sea level. These older rocks were mainly augite-bearing but some hornblende-bearing rocks were also exposed to erosion. From time to time volcaniclastic deposition ceased and calcareous sediments were deposited and rapidly covered again with volcaniclastic detritus. Some parts were probably exposed subaerially and the deposition of nonpillowed lavas occurred. This area was then tectonically tilted.

Later the calcareous volcaniclastic sandstones and siltstones of the Yauco Mudstone were deposited unconformably upon the Maricao Basalt. The material was deposited in a tectonically unstable shallow-marine environment and a huge thickness of sediments was able to accumulate. Nearly all of the volcaniclastic material is epiclastic in origin with minor direct contributions from a volcanic source, as indicated by sporadic, thin tuff beds. In periods of quiesence limestone was deposited,this was sometimes broken up, probably by storms, and redistributed and mixed with volcaniclastic material.

After this, an influx of massive, epiclastic hornblende-bearing breccias and conglomerates to the basin caused a cessation of the Yauco Mudstone deposition. Little volcanic activity, at least in the southwest quarter of the Monte Guilarte quadrangle, accompanied the deposition of the unnamed hornblende breccia unit. The bulk of the volcaniclastic sediments was derived mainly from older volcanic and hypabyssal rocks which were exposed above sea level. Some acidic rock fragments were part of the volcaniclastic debris during this time; thus, for the firs time in the volcanic-sedimentary sequence of the southwest quarter of the Monte Guilarte quadrangle acidic rocks were exposed and were being eroded. From time to time the influx of epiclastic material decreased and calcareous sediments were deposited. The decreasing thickness of the unnamed hornblende breccia unit toward the west tends to indicate that the source was probably to the east or north. Following the deposition of the unnamed hornblende breccia unit, the deposition of the Yauco Mudstone continued. This relationship of the unnamed hornblende breccia unit within the Yauco Mudstone may indicate that the surrounding areas were undergoing some tectonic activity.

Probably at the same time, but in the western corner of the area, minor lava flows of the Sabana Grande Formation were deposited subaerially on the Yauco Mudstone. After this, some reworking gave rise to the interflow sandstones. The unit was rapidly covered with additional marine Yauco sediments.

Later, the sequence was deformed into broad folds followed by the intrusion of the augite porphyry and the horblende porphyry bodies. Subsequent faulting produced the final deformation in the area prior to uplift.

PUERTO RICO AND PLATE TECTONICS

Edgar, Ewing, and Hennion (1971) concluded that the Caribbean crust is a fragment of the East Pacific plate which was wedged between North and South America during their separation from Africa and Europe in early Mesozoic time, but which broke away from the East Pacific plate during late Mesozoic time. They base these conclusions on certain peculiarities of the Caribbean plate such as the smooth oceanic basement surfaces, the lack of symmetrical magnetic anomalies, the dissimilarities of the Caribbean crustal velocities with those of typical oceanic crust, and the overall crustal structure. The Caribbean plate is presently protected from being assimilated into the mantle by the presence of subduction zones plunging beneath the plate on its western and eastern margins. Malfait and Dinkelman (1972), although agreeing with most of the Edgar, Ewing, and Hennion interpretations, disagree with the age of separation of the Caribbean plate from the ancestral East Pacific plate. They believe that the plates separated in the Eocene.

During Cretaceous time or earlier, the Caribbean was a projection of the East Pacific plate and was moving in a northeastward direction. The plate was bounded on the north by a complex trench system in which Cuba and part of Hispaniola were under thrust northward beneath the North America plate. To the east, the Caribbean plate was being thrust over the North America plate. All of this was taking place at the same time (Malfait and Dinkelman, 1972). The Beta Ridge, a southwest trending submarine ridge south of Hispaniola, could represent a vestige of the hinge fault that must have been present separating these two opposite motions. The southern margin of the Cribbean plate was being thrust beneath the South America plate (Malfait and Dinkelman, 1972). Nagle (1974), on the other hand, worked on paired metamorphic belts in Hispaniola and concluded that these metamorphic zones are the best indication of southward subduction before and during Cretaceous time in the Greater Antillies. Iturralde-Vinent (1975), working in Cuba, also proposed a southward dipping Benioff zone from Tithonian (Jurassic) through middle Eocene time. Mattson (1973) also proposed a southward dipping subduction zone for the development of the Greater Antilles. This is in contradiction with that of Malfait and Dinkelman. (Figure 32.).

Apparently during late Cretaceous to Paleocene time, the underthrusting of the Caribbean plate beneath northern South America ceased. A system of right lateral transcurrent faults developed in Eocene time as a result of a change in the movement of the Caribbean plate from a northeast to an easterly direction (Bell, 1972; Malfait and Dinkelman, 1972; Iturralde-Vinent,

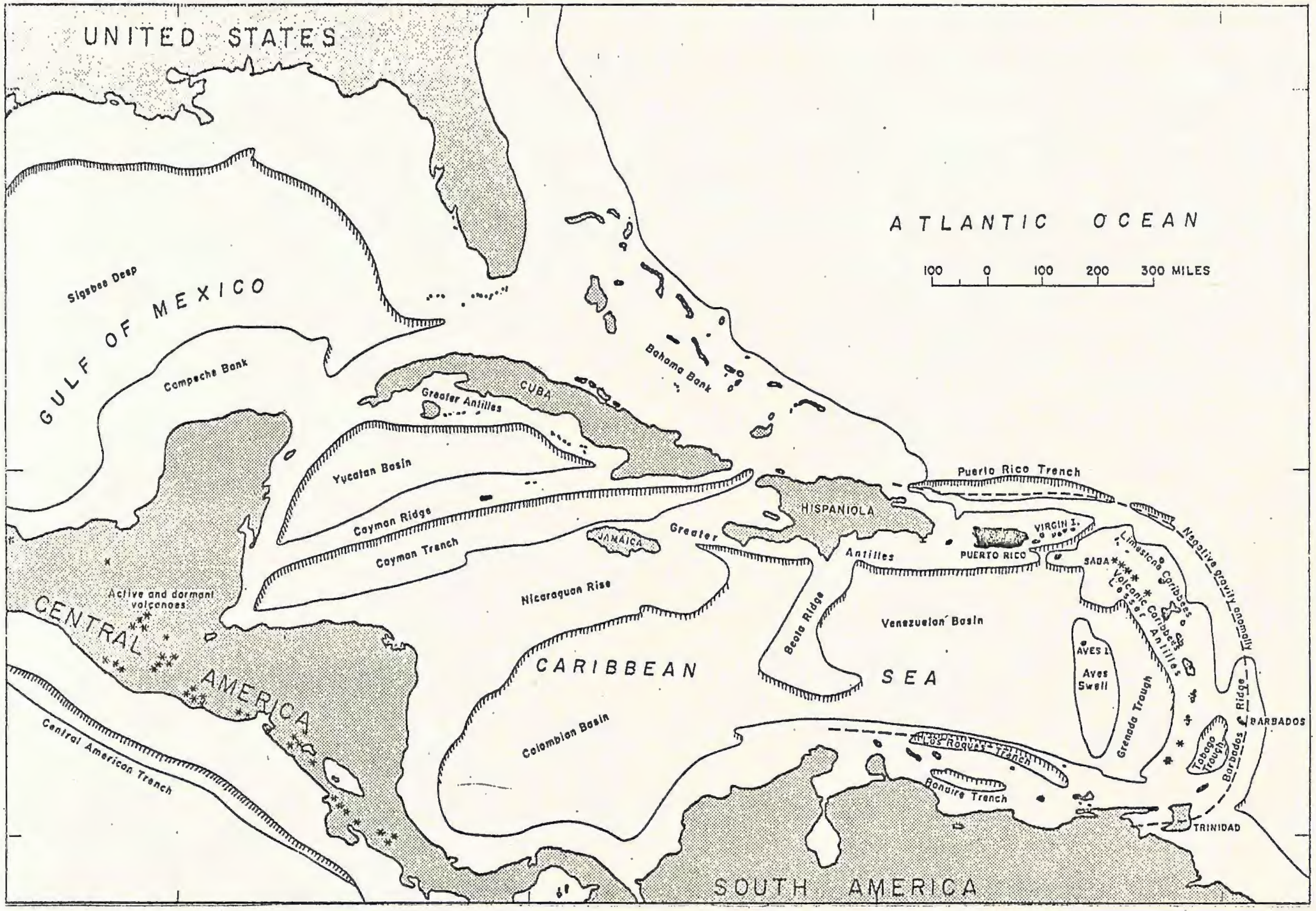

Figure 32. Index map showing location of the major physiographic features of the Caribbean area, from Glover (1971).

1975). These faults are the Oca and Pilar faults in northern Colombia and Venezuela. With initiation of the eastward movement, the Puerto Rico Trench was changed from an active subduction zone to its present role as a transform fault (Malfait and Dinkelman, 1972). Monroe (1968) suggests that the Puerto Rico Trench probably first appeared in Oligocene or late Eocene, but according to Malfait and Dinkelman (1972) this age only represents the initiation of transcurrent movement along the trench. Mattson (1973) indicates that some component of compression is still present as the Puerto Rico Trench remains as a prominent topographic feature.

Meyerhoff and Meyerhoff (1972) believe that the Caribbean area and the adjacent areas have held the same position relative to one another since pre-Jurassic time and probably since pre-Paleozoic time. They claim that ""The new global tectonics", therefore, are not applicable to the Caribbean area". They mention that the northern and southern Caribbean faults do not exist, and that movements along several faults on the northern and southern margins of the Caribbean have been mainly vertical. Nagle (1970) also pointed out that the geological and geophysical evidence indicate that the southern Caribbean fault does not exist. Meyerhoff and Meyerhoff (1972) pointed out that new data from JOIDES drilling the Caribbean area indicate that it may be underlain by Upper Cretaceous crust. This makes the

Caribbean area younger than the surrounding rocks in the North and South America and Cocos plates (Meyerhoff and Meyerhoff, 1972). Based on this, some workers have postulated that the Caribbean has been formed by sea floor spreading. However, no spreading center, or evidence for it has been found in the Caribbean.

Iturralde-Vinent (1975) believes that a northern Caribbean transcurrent fault is not necessary. By the beginning of Oligocene time, the Caribbean plate was separated from the East Pacific plate since the Central America Trench, in which the Benioff zone dips to the east, was formed preventing further access of the East Pacific plate into the Caribbean area (Malfait and Dinkelman, 1972; Iturralde-Vinent, 1975) and therefore, isolating the Caribbean plate between the North and South America plates.

Although the several tectonic models for the origin of the Caribbean area are very appealing in their own ways, no single model has been accepted by workers of Caribbean geology. More detailed studies of the region are necessary for the development of a final model which will answer and satisfy the unsolved questions and problems of the geology of the area.

PUERTO RICO AS PART OF AN ISLAND ARC

Puerto Rico is apparently part of a typical island arc; a gravity low is located between the island and the Puerto Rico Trench and a gravity high is located on the island (Garrison and others, 1972). The gravity low is believed to be caused by the accumulation of oceanic sediments which have been scraped off as the subducted plate sank into the mantle; the gravity high is believed to be caused by the descending, colder, denser plate (Carmichel, Turner, and Verhoogen, 1974).

The island seems to have evolved from an early tholeiitic stage through a calc-alkaline stage (Miyashiro, 1974; Ringwood, 1974). The tholeiitic stage is represented by the amphibolites of the Bermeja Complex in the southwestern part of the island (Donnelly and others, 1971; Tobisch, 1968), and the calc-alkaline stage is represented by the rest of the volcanic rocks (Nelson, 1968; Lidiak, 1965). Ringwood (1974) suggested that the early tholeiitic stage is due to the dehydration of amphibolite in the Benioff zone, which in turn causes partial melting of the pyrolite wedge; this forms magmas which differentiate under high water pressure producing the rocks of the early tholeiitic stage. As subduction continues, partial melts are produced and fractionate by the crystallization of eclogite and amphibolite producing the late calc-alkaline phase.

The volcanic and sedimentary rocks of the southwest quarter of the Monte Guilarte quadrangle give an idea of the stage of development of the arc. Most of the volcanic and hypabyssal rocks are basic to intermediate in composition, with the latter probably being more abundant. This tends to indicate that the arc was relatively mature, with andesite and dacite the dominant rock types by Late Cretaceous time (Baker, 1960; Miyashiro, 1974). The intermediate and felsic rock fragments in the upper part of the volcanic-sedimentary sequence tend to indicate that by this time felsic rocks were being eroded, probably to the north and/or east.

The volcaniclastic sedimentary rocks are mainly shallow-water marine deposits and were formed by the erosion of pre-existing rocks. This was carried out in the absence of major explositve volcanic activity. Glover (1971) reported that the volcanogenic rocks of Cretaceous age of the Coamo area, to the east of the Monte Guilarte quadrangle, were mainly of deep-water marine origin with explosive volcanic eruptions. These volcanic centers shifted with time in an apparently random fashion. Glover (1971) also pointed out that 1) most of the pyroclastic debris was deposited by turbidity currents, submarine pyroclastic flows, submarine slides, and by direct fallout onto the ocean floor; and 2) there is a lack of epiclastic rocks in the Coamo area. Mattson (1960) reported that there was abundant volcanic activity during the deposition of the Upper Cretaceous rocks in the Mayaguez area, to the west of the Monte Guilarte quadrangle. In the mapped area, with the exception of the Rio Loco Formation, there are relatively few lava flows and little pyroclastic material, perhaps indicating that most of the major centers of volcanic activity in Late Cretaceous time were located to the east and west of the mapped area (Mattson, 1960; Glover, 1971). This, coupled with the paleontological evidence, seems to suggest that southwestern Puerto Rico had a shallow-water marine environment with deeper water to the east.

CONCLUSIONS

1. The bulk of the volcaniclastic material is probably epiclastic in origin, derived from pre-existing rocks.
2. With the possible exception of the Rio Loco Formation, most of the rock units in the mapped area were deposited in a tropical shallow-water marine environment with some periods of exposure above sea level.
3. Little or no explosive volcanic activity was going on during the deposition of most of the rock units.
4. The Bermeja Complex, which was probably exposed during Late Cretaceous time, did not provided a major contribution to the detritus of the mapped area.
5. Probably most of the volcaniclastic material of the southwest quarter of the Monte Guilarte quadrangle was derived from the north or east.
6. The intrusive bodies were emplaced into the sequence at a very shallow depth.
7. Some of the alteration observed in the rocks could be due to Cretaceous weathering of source rocks.
8. Structural deformation in the area is predominantly represented by faults and some minor folds.
9. Structural deformation in the area is probably as old as Maestrichtian.
10. Acidic rocks were probably exposed and were being eroded by Late Cretaceous time.

11. Apparently Puerto Rico is part of a typical island arc which was relatively mature by Late Cretaceous time.

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